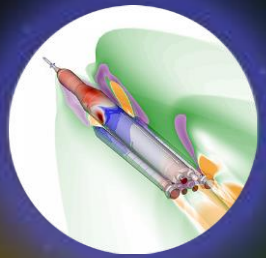
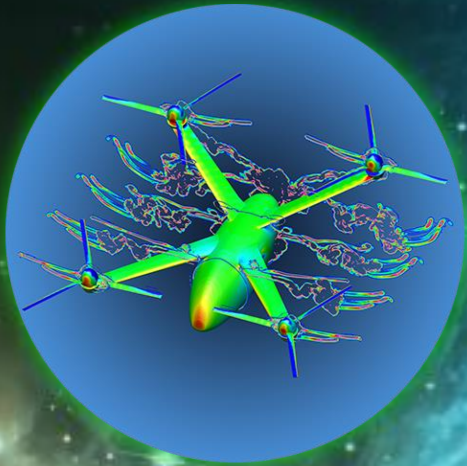
National Aeronautics and
Space Administration





HECC Annual Report FY21

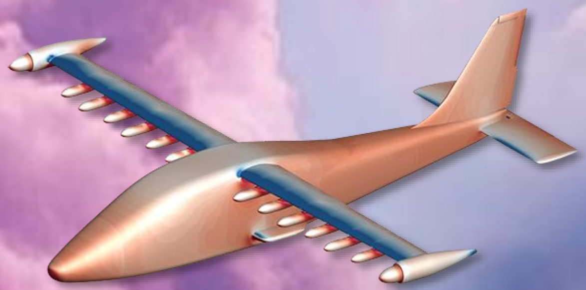
William Thigpen
NASA Advanced Supercomputing Division

25 April 2022

High-End Computing Capability: FY21 Annual Report

- The High-End Computing Capability (HECC) project was established in 2008, with a vision to be an essential partner in enabling rapid advances in scientific and engineering insights and dramatically enhancing NASA mission achievements through world-class HEC resources and services.
- HECC is fulfilling that vision, providing uninterrupted service to scientists and engineers supporting all the agency's mission directorates—delivering a record-breaking 143 million Standard Billing Units (SBUs*)—essential to the success of 780 unique projects in FY21.
- In a second year of challenges surrounding COVID-19 pandemic, HECC also celebrated several major successes, including:
  - **Expanded the Aitken modular supercomputer** with 12 Apollo 9000 "Badger" racks containing 1,536 AMD "Rome" compute nodes—bringing Aitken's theoretical peak performance to 10.76 petaflops.
  - **Released an all-new Endeavour supercomputer**, replacing the original 2013 system with an HPE Superdome Flex system with 32 Cascade Lake processors, increasing the system's compute capability by 483% and enabling quicker turnaround time for user running large, shared-memory capacity jobs.
  - **Increased data storage capacity** with the installation of two DataDirect Networks large filesystems providing 36 petabytes of additional space representing about 50% more capacity and a 100% increase in file transfer speeds to store vast amounts of data for agency projects.

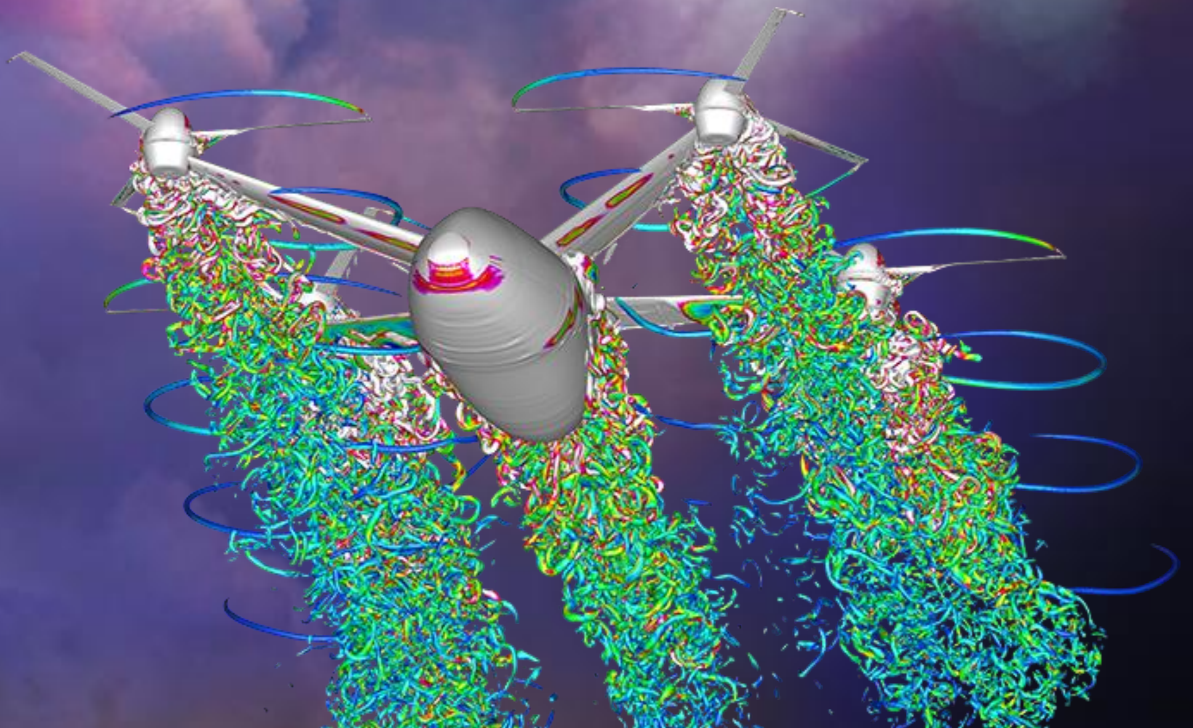
**1 SBU equals 1 hour of a Pleiades Broadwell 28-core node.*



HECC Annual Report FY21

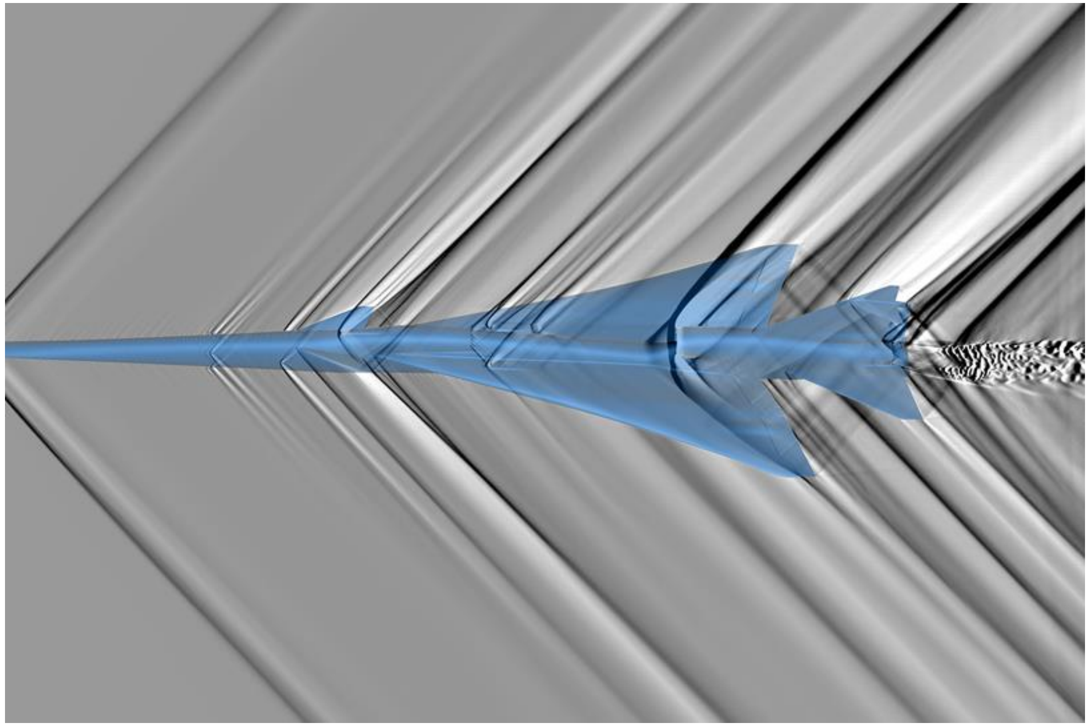
Aeronautics Research Mission Directorate

National Aeronautics and Space Administration



HECC FY2021: Aeronautics Research Mission Directorate

- Many of ARMD's innovative modeling and simulation breakthroughs, critical to NASA's collaboration with aircraft industry partners and attaining the agency's vision for advancing sustainable aviation technology and safety, rely on HECC supercomputing resources and technical expertise.
- The investment in HECC systems and services grew to 166 ARMD projects in 2021, providing scientists and engineers with more than 30 million SBUs* to meet their program objectives.
- Ten representative projects are highlighted, with a focus on developing flow physics models to accurately predict performance for quieter and more fuel-efficient aircraft; and advancing computational capabilities to develop, evaluate, validate, and test next-generation vehicles. These projects contributed to several program level reviews and milestones and produced 30 publications in FY21.
- HECC's collaboration with ARMD will continue to return unique solutions to provide new and efficient options for air travel, such as electric propulsion systems and advanced air mobility vehicles—all for cleaner, safer, more efficient air transportation.



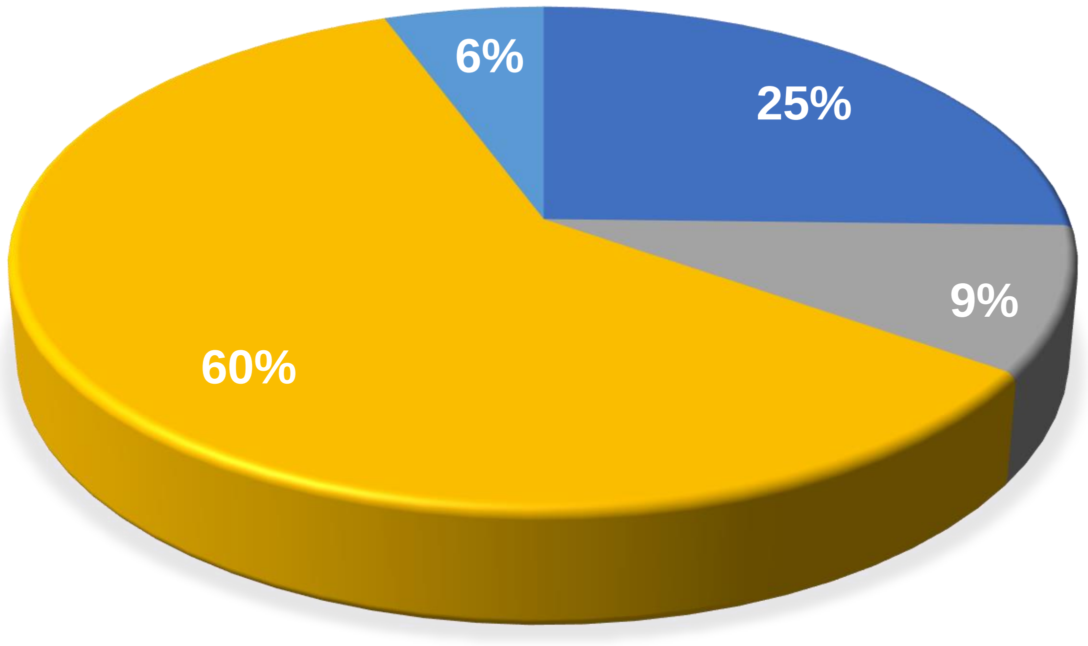
**1 SBU equals 1 hour of a Pleiades Broadwell 28-core node.*

HECC FY 2021: Aeronautics Research Mission Directorate

- **Total Usage: 31,251,520 SBUs**
  - **Number of Projects:** 166
  - **Average CPU Range:** 2,049 – 4,096 CPUs
  - **Average Expansion Factor:** 2.77
  - **Agency Reserve:** 6,556,137 SBUs
  - **Share:** 24,622,214 SBUs
  - **Usage as Percent of Share:** 127%
  - **Usage as Percent of Share + Agency Reserve:** 100%

- **By ARMD Program**
  - **Transformative Concepts:** 18,625,243
  - **Advanced Air Vehicles Program:** 7,933,925
  - **Integrated Aviation Systems Program Office:** 2,930,134
  - **Aeronautics Evaluation and Test Capabilities:** 1,759,478
  - **Airspace Operations and Safety Program:** 2,740

ARMD FY21 Usage



**1 SBU equals 1 hour of a Pleiades Broadwell 28-core node.*

Large Eddy Simulations for Certification by Analysis

Summary

- Engineers at NASA Ames used their Launch Ascent and Vehicle Aerodynamics (LAVA) code to run several wall-modeled large-eddy simulations (WMLES) of non-academic flow configurations involving large-scale geometry and shock-driven boundary layer separation. The simulations, run on the Aitken supercomputer, provided excellent quantitative and qualitative accuracy for aircraft in landing, takeoff, and cruise, as well as high-speed buffet flight conditions.

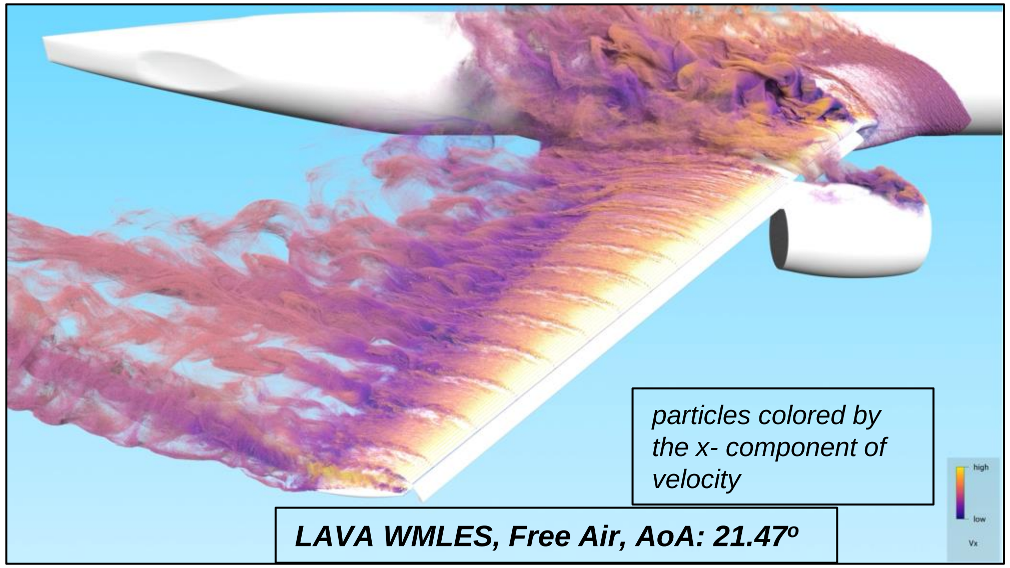
Key Results

- The primary focus of the WMLES group was to study the High-Lift Common Research Model (CRM-HL). The team developed and leveraged new WMLES capabilities within LAVA to demonstrate the potential for scale-resolving simulations to address major deficiencies of legacy closure modeling for high angle-of-attack flows seen during landing and takeoff. WMLES was shown to accurately capture both the loads and the overall flow topologies when compared with the experimental data.

Role of HECC

- LES requires high spatio-temporal resolution, which can only be achieved via the petascale computing resources provided by HECC. Aitken's new AMD Rome nodes are particularly useful for these simulations—by utilizing more than two billion grid points on 100–150 Rome nodes, each angle-of-attack simulation can be completed in just over 24 hours.

BENEFIT: HECC resources were heavily leveraged by the LAVA group to develop and demonstrate one of NASA's premiere capabilities for scale-resolving simulations of wall-bounded turbulence involving complex, realistic geometries. WMLES has emerged as the most promising approach to meet the agency's CFD Vision 2030 goal of Certification and Qualification by Analysis (CQbA).



LAVA WMLES, Free Air, AoA: 21.47º

"LAVA WMLES have served to meet a critical pacing item for CQbA, and the latest generation HPC resources provided by HECC have played a paramount role in these successes." — *Cetin Kiris, NASA Ames Research Center*

Airframe Noise Simulations for Supersonic Transport

Summary

- Accurate predictions to estimate airframe noise characteristics for supersonic aircraft flying at low speeds are crucial to parametric studies that evaluate competing concepts to identify the most viable low-noise configurations. Researchers at NASA Langley performed high-fidelity simulations of a 15%-scale model of a generic low boom concept (GLBC) in landing configuration to determine the airframe noise sources associated with the vehicle and to predict its far-field noise signature on the ground.

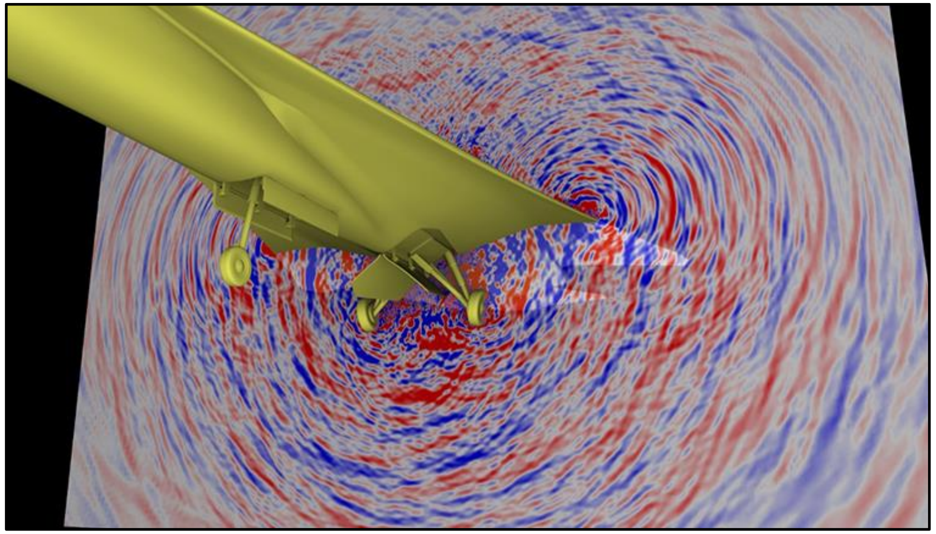
Key Results

- Validated the computed low-speed aerodynamic characteristics of the GLBC via comparison with existing wind tunnel measurements obtained at Langley.
- Identified primary and secondary airframe noise sources of the GLBC; and determined individual and combined airframe source contributions to the far-field noise footprint of the aircraft that affect community noise on the ground.
- Leveraged the predicted noise levels to ascertain the accuracy of semi-empirical airframe noise models used by NASA to conduct system-level acoustic analyses of commercial supersonic transports.

Role of HECC

- HECC resources were indispensable for conducting these large-scale simulations within the allocated time and schedule.

BENEFIT: As part of NASA's collaboration with the FAA and the International Civil Aviation Organization, results from this work were used to identify major airframe noise sources for this class of aircraft and to reduce the uncertainties associated with semi-empirical models used in system-level noise prediction studies.



"The animations produced by the HECC visualization group were instrumental to gain insights into the time-dependent flow structures that generate airframe noise and the propagating sound field in the vicinity of the supersonic aircraft."
– Mehdi Khorrami, NASA Langley Research Center

Scale-Resolving Simulations for Turbulence Models

Summary

- Researchers at the University of Colorado Boulder are applying a unique approach to a broad spectrum of spatial and temporal scale-resolving simulations to identify modeling successes and failures. Rather than promoting a particular model as the key to improving engineering prediction, they are assessing lower fidelity models with the next higher fidelity model under matched flow conditions, then employ physics-based insight and data-driven approaches to improve the accuracy of the lower fidelity model.

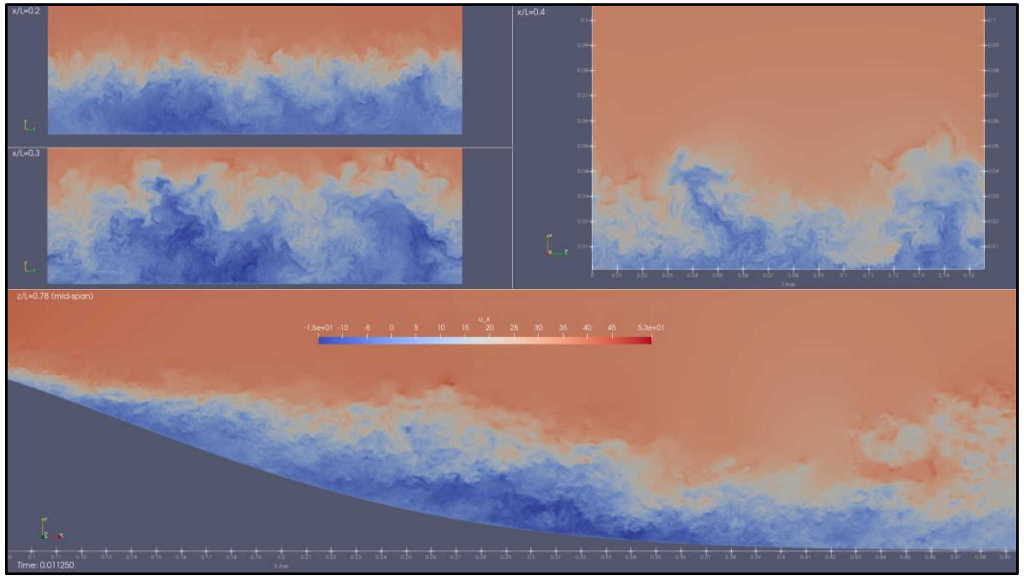
Key Results

- The team conducted direct numerical simulations (DNS) of a turbulent boundary layer over a Gaussian-shaped "Boeing Bump" at two Reynolds numbers. Their results provided valuable insight into why state-of-the-art Wall-Modeled Large Eddy Simulation (WMLES) and Wall-Resolved Large Simulation (WRLES) models fail both in the adverse pressure gradient region where separation is poorly predicted and in the strong favorable pressure gradient regions, which often occur far upstream of separation.

Role of HECC

- HECC resources enable very large core-count runs (972 nodes, using 38,880 Skylake processors) for five days to advance the DNS of the Boeing Bump at a Reynolds number of 2 million.

BENEFIT: This research identifies deficiencies in existing turbulence models and proposes new, more accurate models that can be used to improve fuel efficiency and better control authority.



"HECC resources are critical to the success of this project because these are such large simulations. We also run smaller cases on the same geometry to assess current model performance."
– Kenneth Jansen, University of Colorado Boulder

Uncertainty Modeling for Sonic Boom Noise Generation

Summary

- In order to predict sonic boom noise of supersonic aircraft, researchers from NASA's Glenn Research Center used agency supercomputers to study the effects of uncertainty of various model parameters against ground noise predictions. Understanding the importance of each input in a quantitative manner will allow research and development work to concentrate on aspects that have the most impact on results.

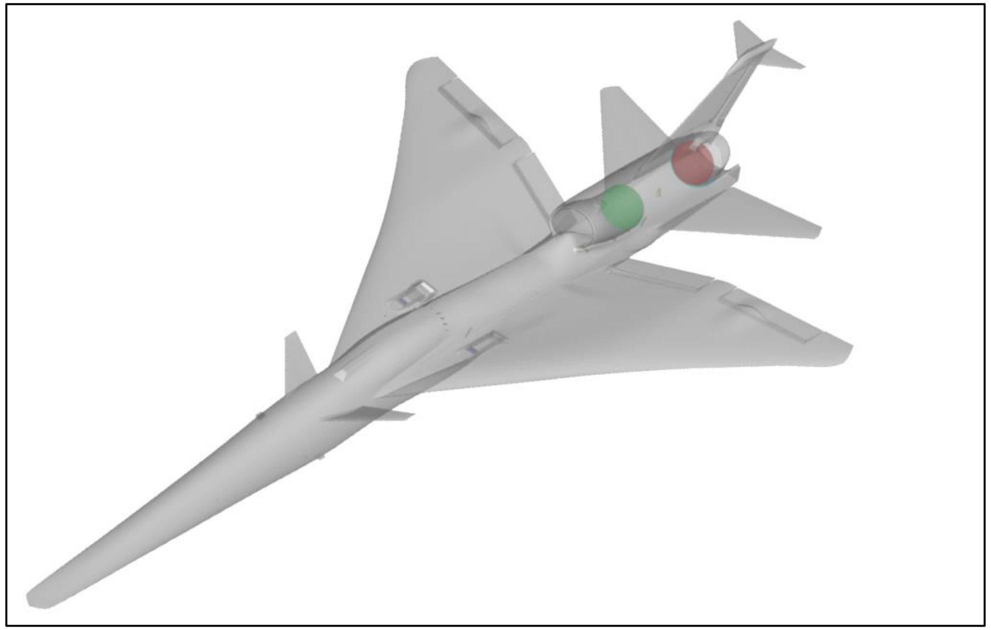
Key Results

- The researchers performed uncertainty modeling of sonic boom noise generation from commercial supersonic transport aircraft using Spalart-Allmaras turbulence modeling parameters, Mach number, angle of attack, and altitude using the Uncertainty Quantification with Polynomial Chaos Expansion (UQPCE) code, as well as NASA Langley's FUN3D solver. The results showed that angle of attack had the most impact against ground noise, followed by altitude and then Mach number.

Role of HECC

- The grid adaptation for shock capturing needed to be independently applied for each condition, with the final mesh for each set using approximately 420 million cells. Running 42 cases at this size was a feat only possible with HECC resources. The group also developed several Ruby and PBS codes to improve their job efficiency, which have been shared with other teams.

BENEFIT: This uncertainty quantification study showed that similar modeling methods, particularly, the agency-developed UQPCE code, can be widely applied to other parameters to assess their effect against sonic boom noise generation, and contribute meaningfully to NASA's ability to design a certification-by-analysis procedure.



"Running all 42 cases for the uncertainty model with such a large geometry was made possible by HECC resources."
– Makoto Endo, NASA Glenn Research Center

CFD Simulations of the X-57 Electric Propulsion Concept

Summary

- CFD researchers at NASA Langley are working with industry partners to demonstrate increased efficiency of the all-electric X-57 Maxwell concept airplane. The primary goal is to demonstrate a 4–5 times reduction in energy usage by reducing the wing area, improving the efficiency of both the distributed electric propulsion (DEP) motor and the wing-tip propellers.

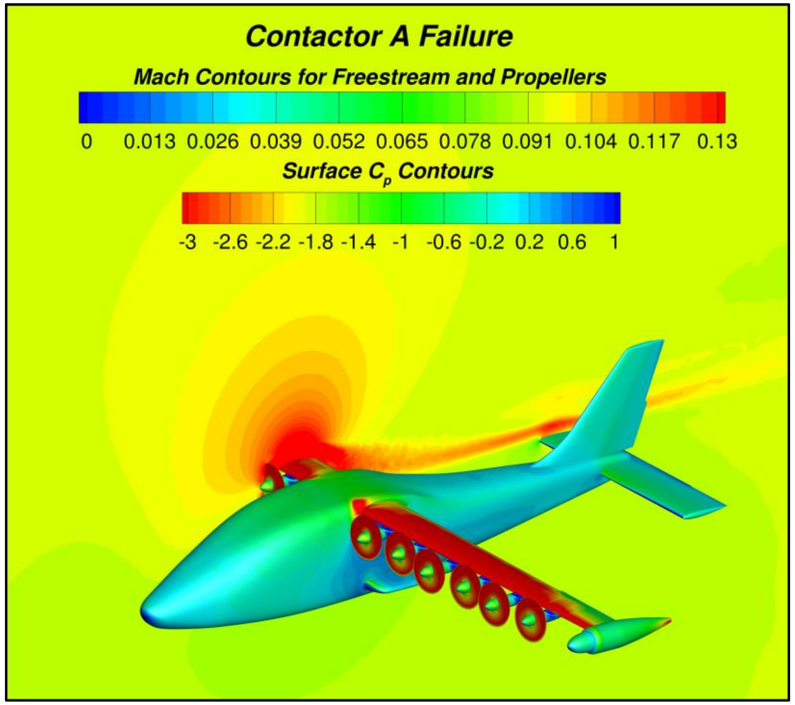
Key Results

- This year, the Langley team delivered 351 CFD solutions to NASA Armstrong for the development of an X-57 aerodynamic database and flight simulator: 281 solutions investigating two alternating failed DEP motor scenarios; and 70 solutions to support modeling of the aircraft's dynamic characteristics in sinusoidal motion.
- Results for the motor failure scenarios from three NASA centers compare well for angles of attack less than 10 degrees. Results for the sinusoidal motion scenarios at unpowered conditions compared well in pitch and roll direct damping derivatives, with some differences in the yaw damping derivative.

Role of HECC

- The Langley team utilized the Pleiades supercomputer to handle the large grid sizes, solution complexity, and number of solutions for their CFD simulations—which used 1 million SBU hours, meshes up to 275 million cells, and approximately 900 processors per solution.

BENEFIT: These simulations provide critical data for flight simulators, airworthiness assessments, and safety analyses so that test pilots can prepare for the possibility of motor system failures prior to and during real X-57 test flights.



"The NAS facility and HECC resources were critical for computing solutions with multiple CFD codes to estimate the uncertainty in results at high angles of attack."
– Karen Deere, NASA Langley Research Center

Aerodynamics Evaluation of NASA Check Standard Model

Summary

- As part of NASA's Aeroscience Evaluation and Test Capability Portfolio, researchers at NASA Ames, Langley, and Marshall are evaluating the accuracy of computational fluid dynamics (CFD) methods for predicting the flow over models inside Unitary Plan Wind Tunnel #2 at NASA's Langley Research Center. The Check Standard Model (CSM) is used by wind tunnel staff to track the test-to-test repeatability of measurements over long periods. The evaluation project team is using the CSM as one of their seven cases.

Key Results

- Large grids are required for simulating flow through the wind tunnel and over the model. The wind tunnel and CSM were built long before computer- aided design tools were available, and the evaluation teams found many discrepancies between the drawings and reality. One of those made its way into the wind tunnel definition but subsequent analyses showed minimal effects for the seven cases. Existing data from the last 10 tests of the CSM will be used for comparisons. The CSM evaluation will be complete in FY22.

Role of HECC

- These steady simulations require up to 240 million grid points, with more than 250 cases needing to be run using both LAVA and Kestrel codes. The number of cases required for this work could not have been done without access to HECC resources.

BENEFIT: The CFD evaluation project will provide an ongoing demonstration of how well CFD can simulate supersonic flow over models in the NASA Langley wind tunnel, in addition to helping the agency to determine whether to keep the facility and how to best improve both experimental and computational capabilities.

"The HECC resources at the NASA Advanced Supercomputing (NAS) facility have truly enabled the computations necessary for this evaluation."
– Jim Ross, NASA Ames Research Center

Wall-Modeled Large Eddy Simulation for the NASA CRM

Summary

- Aerospace engineers at Stanford University used HECC resources to demonstrate the technology-readiness level of wall-modeled large-eddy simulations (WMLES) and to extend its applicability to realistic 3D external aerodynamics configurations by running WMLES of the NASA's High-Lift Common Research Model (CRM) using the finite volume solver charLES, developed at Cascade Technologies.

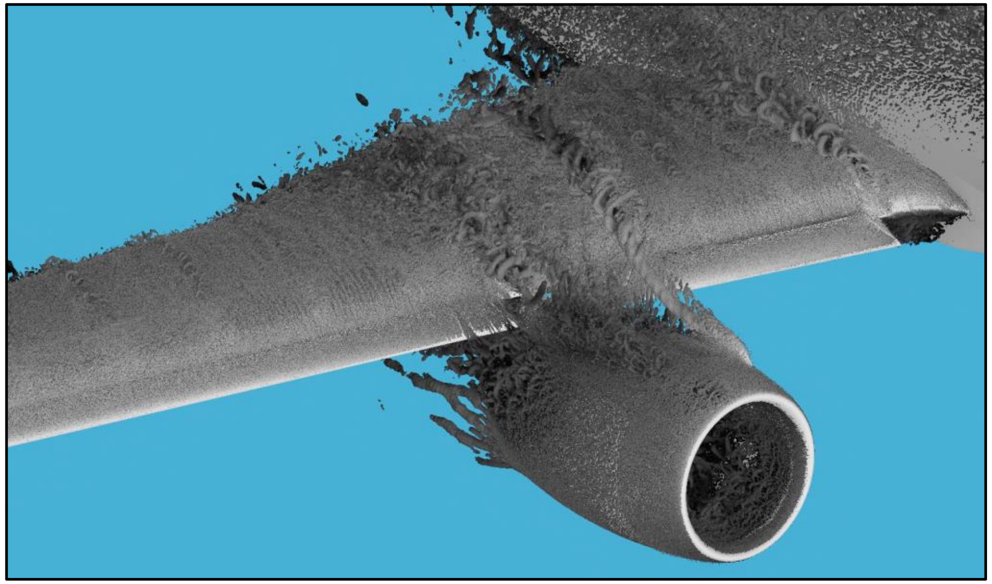
Key Results

- The CRM simulations provided valuable insight into the grid convergence behavior of LES and the resolution requirements associated with predicting lift, drag, pitching moment, sectional pressures, and surface skin friction.
- Including wind tunnel effects proved to be critical for predicting stall.

Role of HECC

- Simulations across the lift curve were carried out at seven angles of attack at three different grid resolution—coarse, medium, and fine—on the Pleiades supercomputer. The simulations ranged from approximately five points to 40 points per boundary layer thickness at the trailing edge, with each run requiring 2,000 or more cores.

BENEFIT: This work supports the Grand Challenge Problem 1 posed by the NASA CFD Vision 2030 report: "LES of a powered aircraft configuration across the full flight envelope"; and directly benefits NASA's efforts to mature enabling technologies for Certification by Analysis.



"NASA's HECC resources were critical to completion of our research objectives and project milestones. In addition, our group appreciates the help and expertise of HECC support staff." – *Konrad Goc, Stanford University*

High-Fidelity Simulations for Multi-Rotor Urban Air Mobility

Summary

- Researchers at NASA Ames are developing new tools and datasets for designing Urban Air Mobility (UAM) concept vehicles, using the CAMRAD II/OVERFLOW loose coupling methodology for studying the agency’s quadrotor and quiet single-main rotor (QSMR) air taxis.

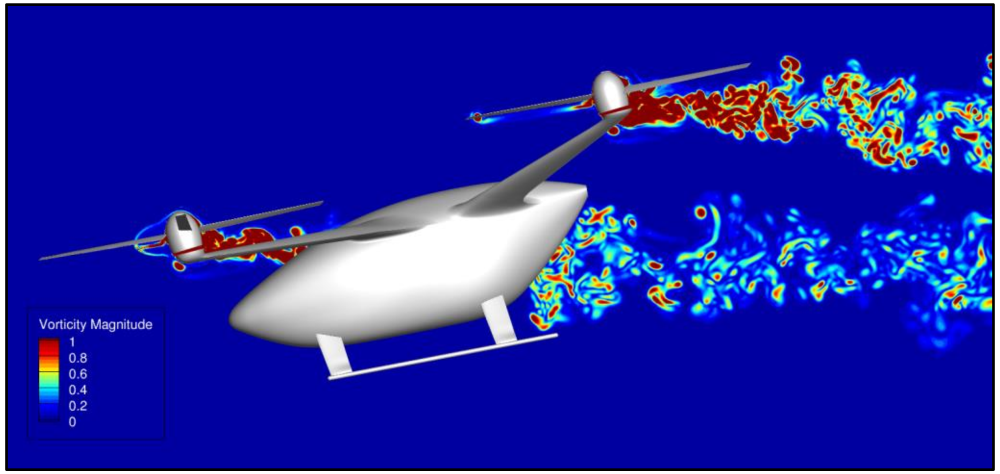
Key Results

- Generated high-fidelity computational fluid dynamics (CFD) simulation data for UAM concept vehicles, at various flight conditions, to compare and improve the empirical models used by current UAM vehicle design tools.
- Calculated the rotor power reduction in edgewise flight of quadrotor “rotors-only,” for different rotor vertical separation distances between front and rear rotors. Simulations showed that the highest rotor power reduction (7%) was obtained for vertical separation—a distance of z_rear – z_front = 0.35R.
- Analyzed airloads and performance of the quadrotor complete vehicle (Dz= 0.35R) in hover, climb, and cruise; and assessed the effects of the airframe and other components on forces and moments.

Role of HECC

- HECC supercomputers were key to the feasibility of this project, running with 2,000 processors for 5–10 days, with hundreds of thousands of grid points per configuration, dozens of simulations, and different flight conditions.

BENEFIT: Generating high-fidelity CFD simulations of Urban Air Mobility concept vehicles supports NASA’s Revolutionary Vertical Lift Technology (RVLT) project goal to focus and guide research activities in aircraft development for emerging aviation markets.



“HECC resources are absolutely necessary to perform this work. The high-fidelity CFD computations are only possible thanks to NASA's supercomputers. In addition, the visualization experts have always so helpful.”
– Patricia Ventura Diaz, NASA Ames Research Center

Design Optimization for Fuel-Efficient Aircraft Concepts

Summary

- Aeronautics researchers from the University of Michigan and NASA Glenn are using HECC supercomputers to perform aeropropulsive design optimization, a promising solution to improve the design of fuel-reducing technologies such as boundary layer ingestion.

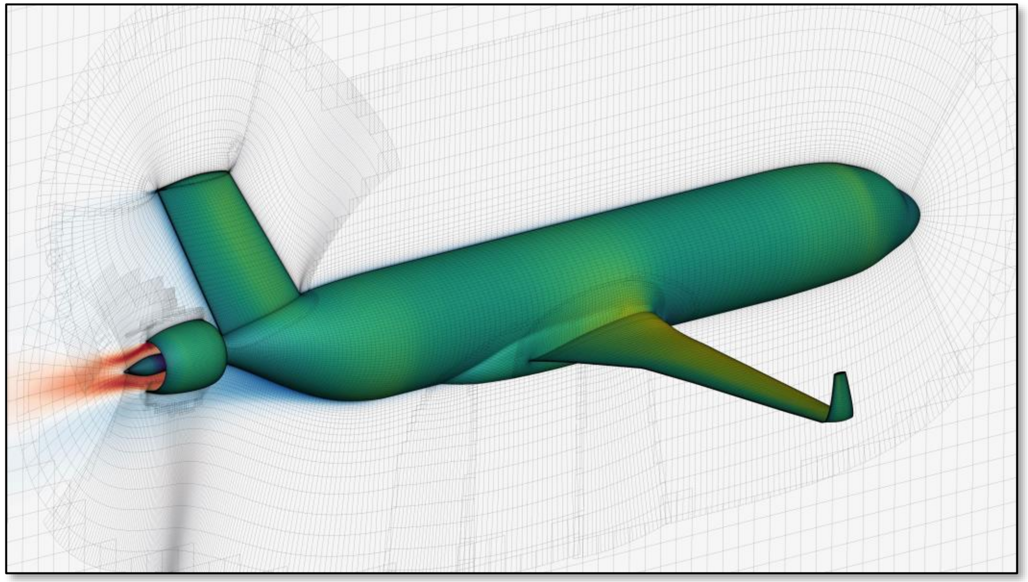
Key Results

- The team developed and tested two robust aeropropulsive models that can be used with gradient-based design optimization tools, and then applied these methods to advanced aircraft configurations such as NASA's Single-aisle Turboelectric Aircraft with Aft Boundary-Layer Propulsion (STARC-ABL) concept. Their advancements in aeropropulsive design optimization will accelerate the design and integration of future advanced propulsion systems.

Role of HECC

- Each of the 18 STARC-ABL computational fluid dynamics (CFD) based optimizations took one day on up to 400 processors to complete. The speed and capability provided by HECC resources allowed the researchers to study a range of designs. This was instrumental in the development of the CFD-based performance data of the STARC-ABL concept.

BENEFIT: These design optimization studies are being used to guide NASA's future research efforts on advanced propulsion systems, and to develop software libraries that will enable simulation-based design optimization with NASA's OpenMDAO framework.



"HECC resources have been essential to our work. To our knowledge, these are the first examples of such optimizations in literature."
– Anil Yildirim, MDO Lab, University of Michigan

Numerical Simulations of Turbulent Heat Transfer

Summary

- Engineers at NASA Glenn used HECC resources to develop and evaluate computational fluid dynamics (CFD) techniques for analyzing turbulent flows that occur in the components of air-breathing propulsion systems. These methods include Reynolds-averaged Navier-Stokes (RANS) techniques but emphasize scale-resolving simulation (SRS) methods such as large-eddy simulations (LES). Consideration of turbulent heat flux is a focus of this work.

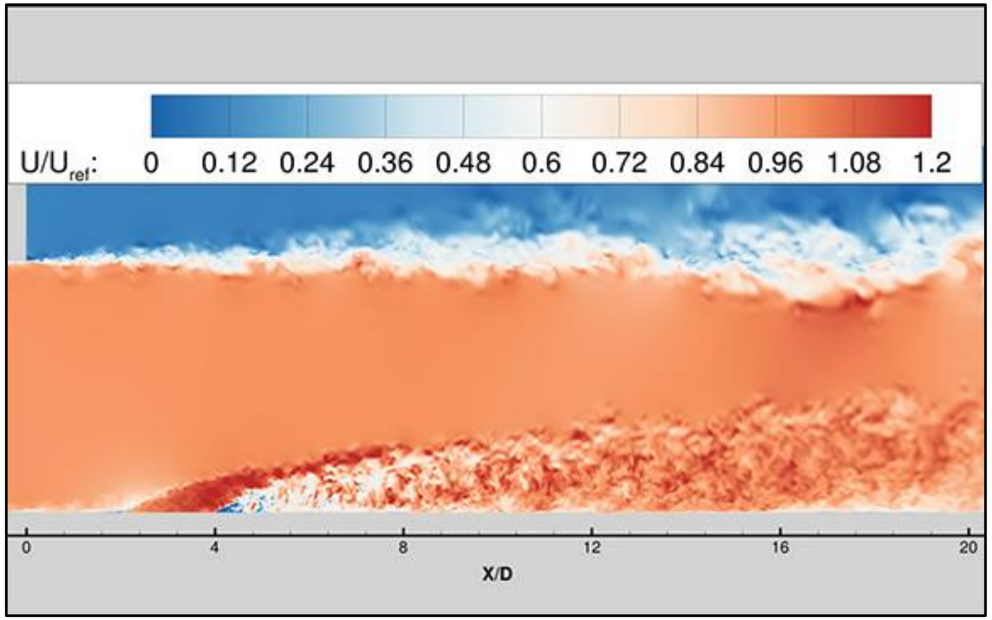
Key Results

- Results are helping to improve understanding of turbulent heat transfer, as well as contributing to best practices and techniques for computing turbulent flows. The team identified deficiencies in RANS-based methods for computing turbulent heat flux—indicating that the gradient-transport hypothesis used to model turbulent heat flux in RANS may be insufficient—and scale-resolving techniques are required to provide improved predictions.

Role of HECC

- Without HECC resources, this work would not have been completed. In order to obtain the turbulent statistics for comparison to experimental data, the scale-resolving simulations each required tens of thousands of cores and long runtimes on Electra and Aitken and used up to 1.5 billion grid points. Each of the final production runs was carried out on 400 Aitken Skylake or Cascade Lake nodes.

BENEFIT: This work supports NASA ARMD's Transformative Aeronautics Concepts Program, through the Transformational Tools and Technologies project, and helps advance CFD technology support of the agency's CFD Vision 2030.

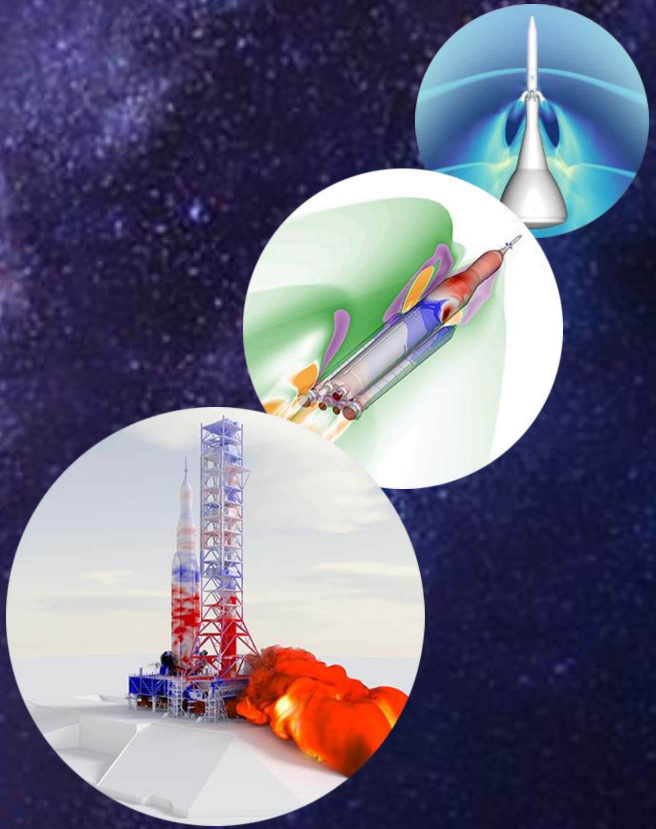


"The project would not have been possible without the availability of HECC compute resources. The simulations also generated a significant amount of data, which the HECC filesystems supported flawlessly."
– Michael R. Borghi, NASA Glenn Research Center

National Aeronautics and
Space Administration

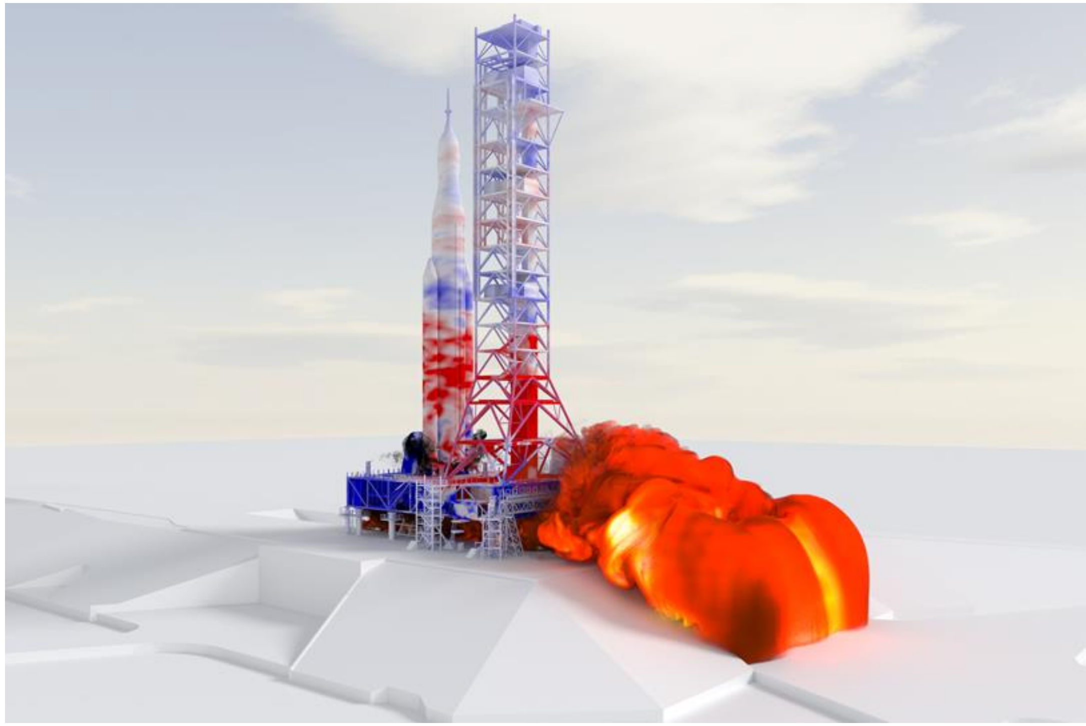
HECC Annual Report FY21

Human Exploration and Operations Mission Directorate



HECC FY2021: Human Exploration and Operations

- NASA’s vision for the Artemis Program, as well as human exploration of Mars and key innovations for safe, sustainable space exploration rely on comprehensive modeling and simulation made possible by HECC supercomputing resources and technical expertise.
- In FY21, the investment in HECC systems and services supported 98 HEOMD, STMD, and NESC projects, providing engineers and scientists with over 30 million SBUs* to meet their program objectives.
- Ten representative projects are highlighted, ranging from simulating the KSC launch environment to support Artemis missions, to predicting aerodynamics of the Mars Sample Return Program’s ascent vehicle—which will launch with samples collected from the planet’s surface—to providing data to the engineers developing human landing systems for the Moon and Mars. These projects contributed to several program-level reviews and milestones and produced approximately 30 publications, presentations, and reports during this period.
- Looking ahead, HECC resources and services will continue to play a key role in Artemis Program missions that will return humans to the Moon—and help pave the way for human exploration of Mars.



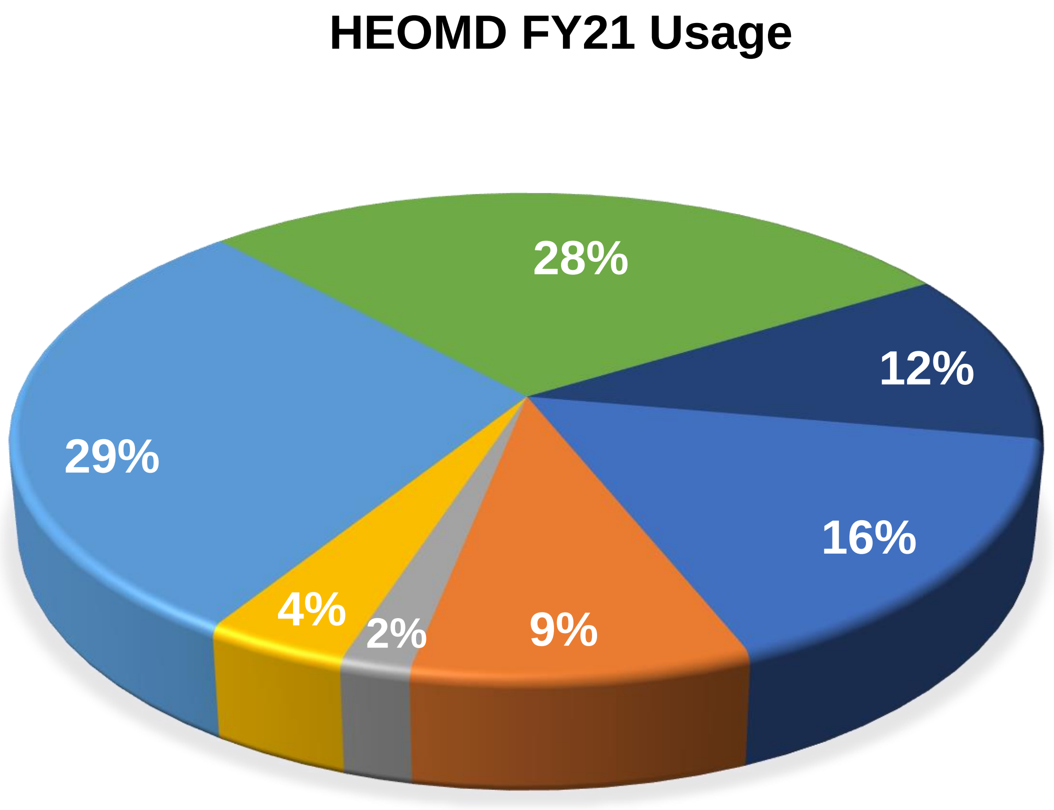
**1 SBU equals 1 hour of a Pleiades Broadwell 28-core node.*

HECC FY 2021: Human Exploration and Operations

- **Total Usage: 30,332,534 SBUs**
  - **Number of Projects:** 98
  - **Average CPU Range:** 2,049 - 4,096 CPUs
  - **Average Expansion Factor:** 2.06
  - **Share:** 26,932,609 SBUs
  - **Usage as Percent of Share:** 113%

- **By Program**

  - **Space Launch System (SLS):** 8,866,072
  - **Space Technology MD** 8,528,589
  - **Ground Systems Dev. & Operations:** 4,889,116
  - **NESC:** 3,476,697
  - **HEOMD Other Program:** 2,783,580
  - **Multi-Purpose Crew Vehicle:** 1,188,435
  - **International Space Station:** 583,625



**1 SBU equals 1 hour of a Pleiades Broadwell 28-core node.*

CFD Analysis of Mars Retrorocket Wind Tunnel Models

Summary

- Supersonic retropropulsion (SRP) technology offers an alternative to using large parachutes to decelerate a spacecraft during atmospheric descent at Mars. Inf FY21, researchers at NASA Langley Research Center (LaRC) developed a computational fluid dynamics (CFD) model to analyze a range of supersonic descent conditions to support planned observational tests in the Langley Unitary Plan Wind Tunnel in 2022.

Key Results

- The Langley team conducted CFD analysis on a range of wind tunnel conditions, including three tunnel Mach numbers, three model thrust levels and attitudes, and six different nozzle designs.
- Information generated during both the CFD and testing processes will be used to: establish CFD best practices for modeling SRP flow fields; inform the planning of future SRP wind tunnel tests with improved testing and measurement methods; compare the total required resources required to execute the wind tunnel test and the CFD simulations; and form the basis for uncertainty estimation of CFD methods at Mars SRP flight conditions.

Role of HECC

- Over 30 million processor-hours were used to complete 300-plus solutions on HECC supercomputers. Each solution typically required meshes with tens to hundreds of millions of grid points and thousands of processor-hours.

BENEFIT: Comparisons between the computational results and wind tunnel test data will form the basis for understanding how accurately and efficiently CFD methods can predict future Mars supersonic retropropulsion vehicle performance.

"Most of these simulations could only be executed on HECC resources due to their large memory requirements."
– Karl Edquist, NASA Langley Research Center

Simulating the Launch Environment at NASA Kennedy

Summary

- To support upcoming NASA Artemis missions from Launch Complex 39B at NASA Kennedy, the Launch Ascent and Vehicle Aerodynamics (LAVA) team at Ames developed a new computational fluid dynamics (CFD) approach for accurately simulating the launch environment, including its water-based sound suppression system. This new CFD capability is both high-order accurate and provably robust, and the team has been working to demonstrate the ability to make the accurate acoustic load predictions necessary for the design and certification of the agency's vehicles.

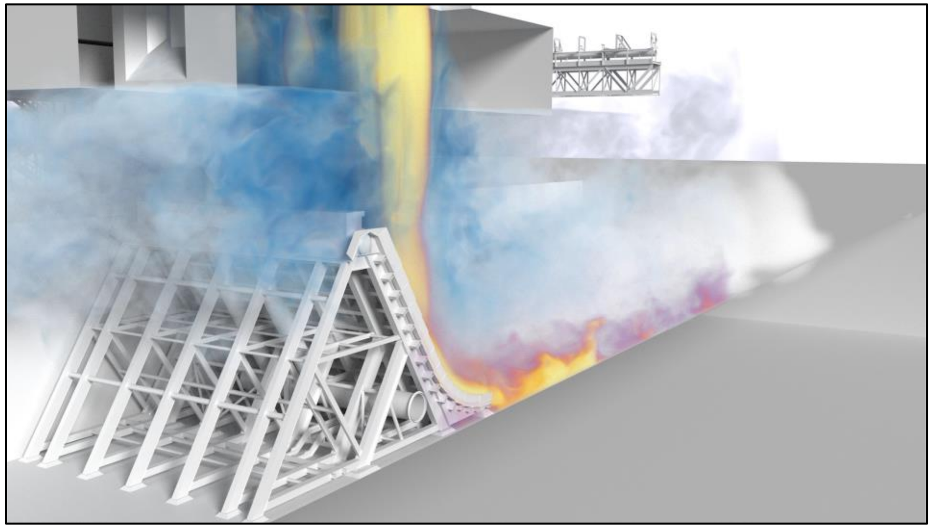
Key Results

- Achieved a more accurate prediction of loads on the vehicle, mobile launcher, and tower structures, and flame trench, by refining the model of the launch environment to include the water effects from the sound suppression system. The multiphase results from this work and new computational capabilities will give a more complete picture of the extreme conditions and reduces the uncertainty associated with traditional prediction methods.

Role of HECC

- Each of the LAVA team's high-resolution simulations of the launch environment used approximately 400–500 million grid cells and ran several weeks on 8,000 cores (Cascade/Skylake). Because these simulations are time dependent, they generate roughly 400 terabytes of data for each run.

BENEFIT: The LAVA team continuously improves and updates NASA's launch environment simulation capability by routinely enhancing the numerical methods, including accuracy, robustness, and time-to-solution. As a result, CFD data are being used to guide project engineers in evaluating real-time, mission-critical design decisions.



"The results and capabilities gained from this work, enabled by HECC resources, will help NASA reduce mission risk—increasing safety and potentially saving significant amounts of time and money."
– Cetin Kiris, NASA Ames Research Center

CFD Support For Orion Launch Abort System Acoustics

Summary

- Computational fluid dynamics (CFD) experts at NASA Ames, in support of the Orion Loads & Dynamics team at Johnson Space Center and the Orion Multi-Purpose Crew Vehicle Program, are providing turbulence-resolving simulation data for the Orion Launch Abort System (LAS) using their Launch Ascent and Vehicle Aerodynamics (LAVA) framework on HECC systems.
- This year, the team simulated eight different launch abort scenarios, investigating the effects of modeling the attitude control motors for abort at supersonic speed, and the impact of the altitude and velocity when abort is triggered, on the strength and spatial distribution of the acoustic vibrations imparted to the vehicle's surface.

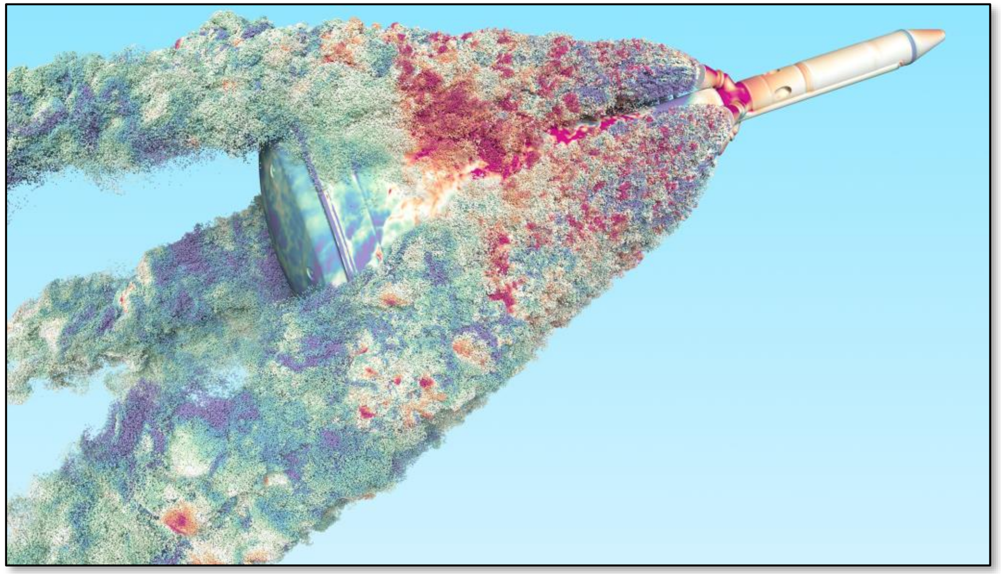
Key Results

- The team demonstrated the importance of altitude for the vibro-acoustic environment on the Orion LAS and produced a technical project report (NASA/TP-20210025053) detailing their findings and lessons learned from their CFD acoustic predictions for over 14 different abort scenarios.

Role of HECC

- Acoustic predictions require a high level of space-time resolution and a long duration, which is only possible with significant HECC resources; each simulation took 7–14 days on 100 Skylake or Rome nodes.

BENEFIT: Significant improvements to the in-house LAVA framework has improved agency CFD acoustic prediction capability, increasing efficiency and reducing turnaround time. These LAS simulations provide vital information to the Orion development teams to help ensure the safety of the crew and vehicle in the event of an emergency.



"LAVA acoustics predictions help reduce risk for the Orion LAS where test data is not available and enhances the safety of Artemis astronauts; it would not be possible without HECC resources."
– Cetin Kiris, NASA Ames Research Center

Simulating Unsteady Forces on the Mars Ascent Vehicle

Summary

- Researchers from NASA Langley used large-scale numerical simulations to predict buffet and aeroacoustics of flight configurations, such as for launch vehicles and aircraft, across a range of speeds.
- To support the design of the Mars Ascent Vehicle (MAV), which will launch with samples collected from the planet's surface, the team was tasked with producing datasets of unsteady forces on the vehicle that were outside the shape and speed range testable in agency wind tunnels.

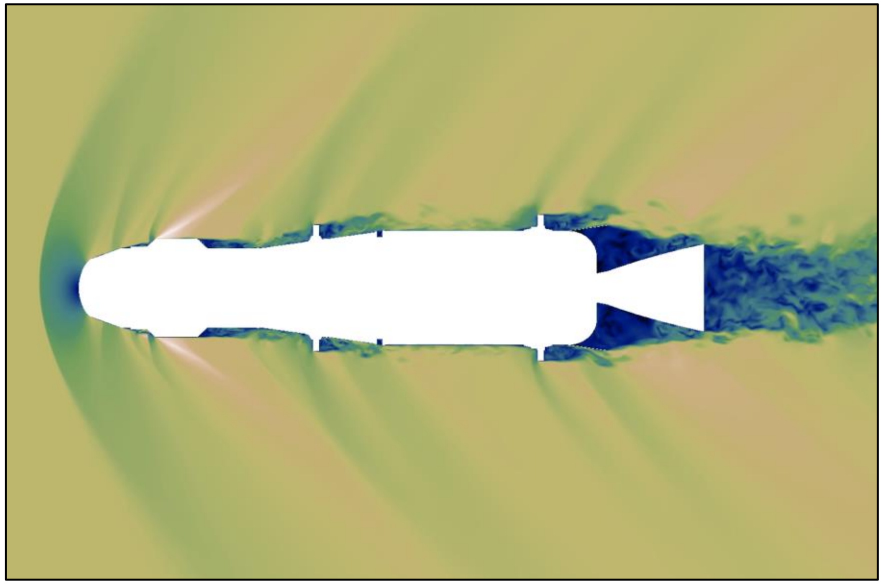
Key Results

- During FY21, unsteady forces on both a preliminary and a later configuration were predicted across a wide variety of Mach numbers through transonic and slow supersonic speeds. The team generated highly detailed surface pressure time histories, which were then processed to yield fluctuating forces on the vehicle. Advanced visualization techniques help show the physics responsible for flow field fluctuations, which help the MAV design team identify and mitigate these forces.

Role of HECC

- The Langley team made extensive use of the Pleiades supercomputer's Cascade Lake graphics processing unit nodes for this work, as well Electra's Skylake nodes for a second, separate set of simulations.

BENEFIT: The large-scale numerical simulations done under this project make it possible to predict buffet and aeroacoustic forces on complex configurations in less time and at a lower cost than what is required to conduct wind tunnel tests, particularly in cases where early assessment of such forces are needed and no experimental data exists.



"HECC is the only high-performance computing resource available to the team that has the speed and capacity necessary to carry out the needed simulations."
– Craig Streett, NASA Langley Research Center

CFD Support for the SLS Ascent Aerodynamics Database

Summary

- Computational fluid dynamics (CFD) experts at NASA Ames play a crucial role in designing and certifying the different families of SLS configurations. Their SLS aerodynamic databases are generated using steady and time-accurate CFD simulations of a high-fidelity model with wind-tunnel data. The simulations focus on the first few minutes of ascent.
- The FY21 SLS ascent simulations included: the Artemis IV Block 1B vehicle during booster separation; early Block 2 booster-separation motor design; a study of potential debris impacts; and the final as-built Artemis I geometry.

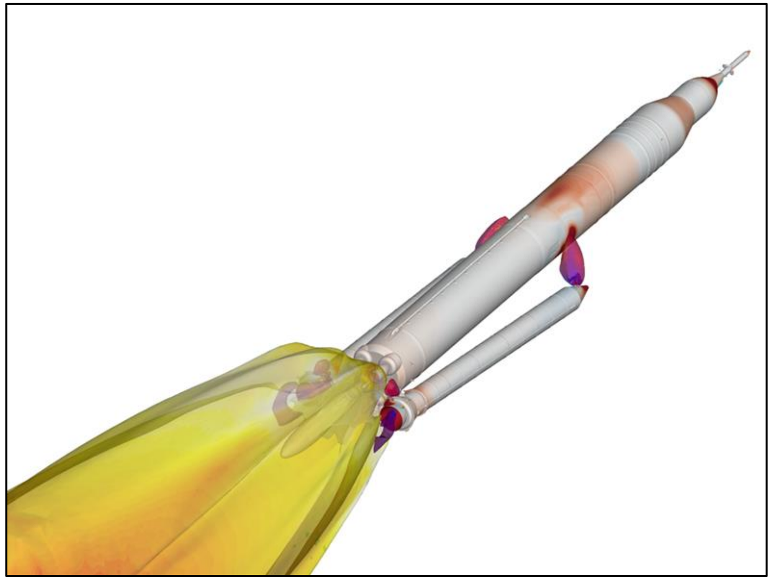
Key Results

- The team at Ames successfully completed flight-readiness assessments for the planned ascent trajectories using aerodynamic models run on HECC resources.
- They also updated the booster separation design for Artemis II from the Artemis I design, with the team's simulations playing a key component in the verification of the updated design.

Role of HECC

- Performing these simulations on HECC resources has saved both time and money for the SLS program, which would otherwise have to rely on more wind tunnel testing.

BENEFIT: The aerodynamics database products are critical to the design, construction, and flight of the Space Launch System family of vehicles. This work directly supports the first two SLS vehicles to be used in the Artemis I and Artemis II missions, in addition to subsequent SLS vehicles.



"The HECC supercomputing resources enabled our team to produce critical aerodynamic data using high-fidelity simulations—including aerodynamics from flow physics that could not be obtained by any other method."
—Stuart Rogers, NASA Ames Research Center

New Methods to Simulate Atmospheric Entry on Mars

Summary

- In order to model the particle-flow interactions during atmospheric entry for future missions to Mars, researchers from Stanford University have developed a high-order discontinuous Galerkin (DG) solver integrated with a disperse particle-flow solver that enables them to better understand the complex physics involved between different flow phases and the entry vehicle as it descends.

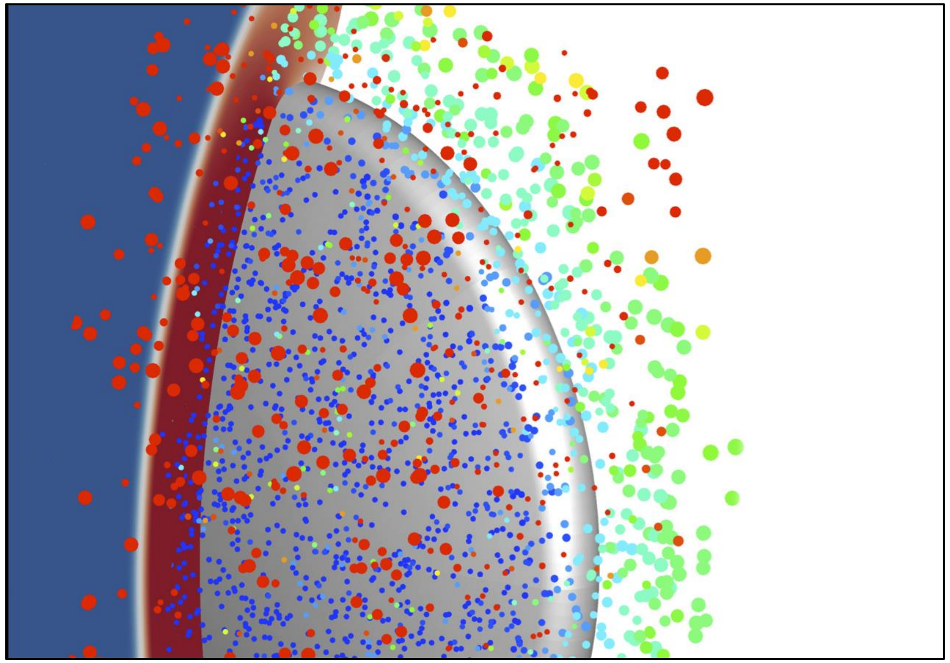
Key Results

- In FY21, the team performed parametric simulations to examine the effects of dusty environments on the heat-flux augmentation during atmospheric entry on a realistic vehicle. NASA currently utilizes the team's disperse-phase model, which has contributed to improving the accuracy of the agency's modeling capabilities. This year, they also worked with the German Aerospace Agency to validate their model and perform simulations of wind tunnel experiments.

Role of HECC

- High-performance computing is critical to perform these large-scale simulations at a reasonable cost. Each simulation ran on thousands of processors on the well-maintained and well-documented Pleiades supercomputer. The large storage capacity available to users was also necessary to regularly save key data files.

BENEFIT: By improving the ability to predict heat-flux augmentation in dusty flows through simulations, we can significantly increase the safety and success of future missions to Mars, especially those requiring substantially higher payloads.



"HECC resources have provided us the ability to develop this code and allowed us to perform the computational simulations necessary to demonstrate this high-order modeling capability." – *Matthias Ihme, Stanford University*

CFD Support for Hypersonic Entry Descent and Landing

Summary

- The Entry Systems Modeling (ESM) project team develops tools and technologies to improve performance, reduce mission risk, and enable new system capabilities across the solar system. This year the team focused on advancing three technology areas to deliver products for entry, descent, and landing (EDL).

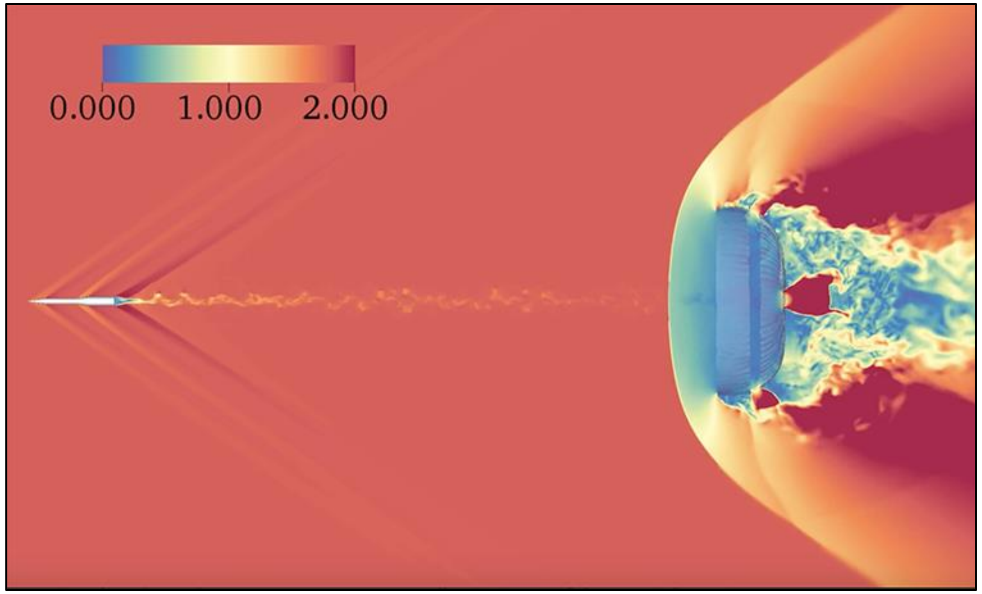
Key Results

- TPS Materials: Developed key tools, including Icarus, PATO, PuMA, and SPARTA. The team infused their TPS tools into active flight projects such as Orion, Dragonfly, and Mars Sample Return missions.
- Shock Layer Kinetics and Radiation: Advanced simulation-based estimates to greatly improve model fidelity and reduce uncertainty, including validation with Hayabusa 2 flight observations. Implemented models in NASA's primary tools for aerothermal analysis so they are infused immediately into the mission design pipeline.
- Aerosciences: Extended the LAVA code as a parachute modeling tool for supersonic parachute inflation relevant to the Mars Sample Retrieval Lander.

Role of HECC

- HECC's investment in new architectures, as well as its support for GPU hackathons, has been instrumental in the success of the ESM project.

BENEFIT: NASA's investment in computational tools will guide next-generation EDL design with quantified uncertainty for performance and risk management. Advanced simulation technology is a key path toward enabling missions to achieve their requirements within acceptable technical risk and cost constraints.



"All of the tools we use are built on high-performance, distributed computing paradigms. Simply put, they would not work without access to HECC resources."
– Michael Barnhardt, NASA Ames Research Center

Developing Human Landing Systems for the Moon and Mars

Summary

- A team at NASA Marshall used HECC resources to run computational fluid dynamics (CFD) simulations in collaboration with developers of several landing systems, including the SpaceX Starship, the Lockheed Martin Ascent Element, and the Dynetics Human Landing System (HLS). The team also supported NASA's Descent System Studies (DSS) by simulating wind tunnel tests of different vehicle concepts in supersonic retropropulsion mode.

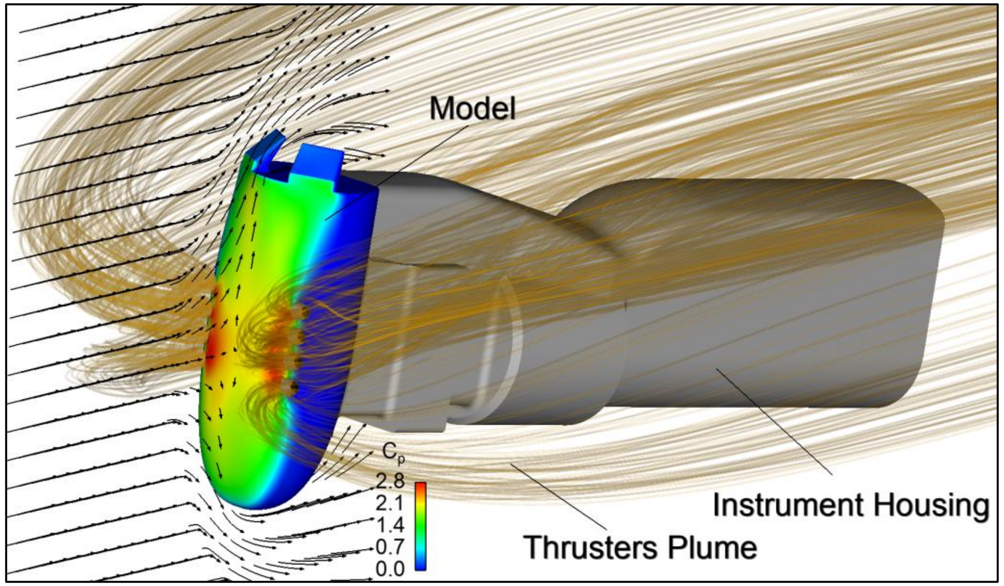
Key Results

- The team completed CFD calculations of the plume induced flow field and thermal environments during lunar descent of the Starship and Dynetics HLS and during ascent for the Martin Ascent Element, providing the commercial design teams with information necessary to evaluate the vehicles.
- For DSS, 30 wind tunnel cases were analyzed for models of two vehicle concepts, different engine configurations, and various wind tunnel operating conditions. Results will be compared against results from different CFD codes as well as against test measurements to address the uncertainties on the current predictive capabilities.

Role of HECC

- The high number of timesteps required for the simulations, and the 400-million-cell computational meshes demanded by the complex flow field induced by plume/ground/vehicle interactions, make HECC resources a necessity.

BENEFIT: This work has a direct influence on NASA human missions to the Moon and on to Mars. Having a complete understanding of the vehicles' environments permits optimization of vehicle designs and increases the probabilities of successful missions.



"Calculations of the size needed for this work can only be accomplished with computing resources such as those provided by HECC." — *Francisco Canabal, NASA Marshall Space Flight Center*

Simulating Launch Environments and Tank Dynamics

Summary

- In support of upcoming missions to space, researchers at NASA Marshall utilized HECC resources to simulate multiple facets of the Space Launch System's launch environment during ignition and liftoff, including ignition overpressure, debris, plume interaction, sound suppression system, liquid engines and propulsion systems, and propellant tank dynamics.

Key Results

- In FY21, the team performed simulations of the SLS vehicle and launch pad environment to assess the effects of high wind conditions for risk and day-of decisions for Artemis I, as well as liftoff debris analysis for SLS Block 1B.
- They developed slosh dynamics simulations for the SLS propellant tanks to support NASA's assessment of vehicle stability in flight.
- The team also supported commercial partners, performing design analysis of Intuitive Machine's Nova-C tank dynamics, analysis of the SpaceX Starship tank dynamics, and model development and validation of tank pressurization and slosh for the Cryogenic Fluid Management Portfolio.

Role of HECC

- Computational fluid dynamics simulations for this work required meshes up to hundreds of millions of cells running for weeks on thousands of processors, and generated terabytes of data stored on HECC resources.

BENEFIT: These analyses are essential to assess the SLS launch environment, propellant tank dynamics, and liquid engine performance, and support both the design and operation phases of future Artemis missions and commercial launches.

"Because we are often simulating a full, integrated vehicle and launch pad or complex multiphase physics that require very large meshes, these analyses would not be possible to complete on schedule without HECC resources."
– Brandon Williams, NASA Marshall Space Flight Center

Developing Aerodynamic Databases for SLS Blocks 1 & 1B

Summary

- As part of the NASA Space Launch System (SLS) goals to transport equipment and astronauts to the Moon and Mars, researchers at NASA Langley are supporting the development of aerodynamic databases, which will be used by other teams to assess vehicle design and performance. The team used computational fluid dynamics (CFD) to produce simulations of the liftoff and transition periods of the SLS flight.

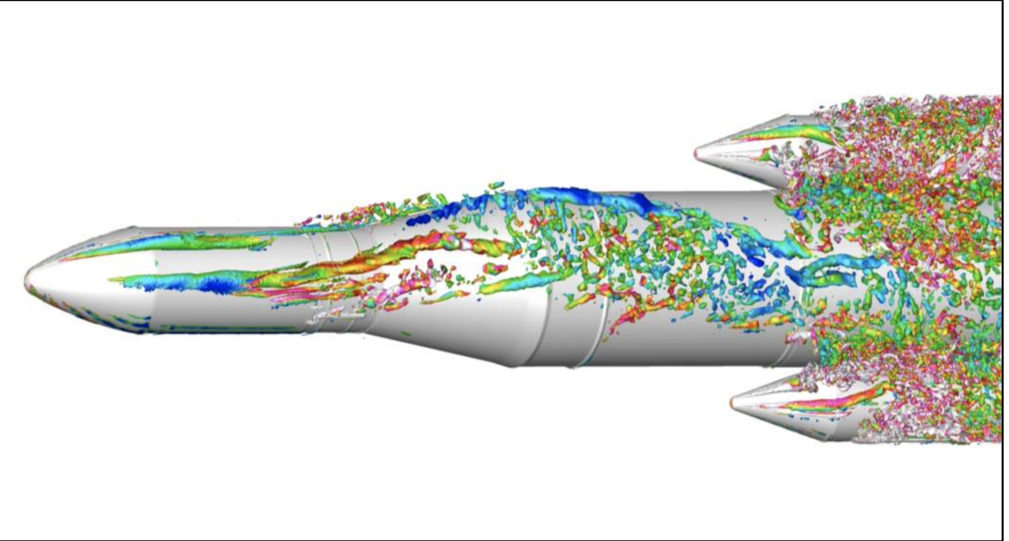
Key Results

- Using their expertise in running liftoff and transition simulations of the SLS Block 1 and Block 1B crew and cargo vehicles, the group developed simulations that include both the vehicle and tower geometries. Each vehicle database required at least 60 transition and 30 liftoff simulations.
- Their success with these simulations led the ground operations teams to request other datasets for evaluating the loads on the emergency hatch, evaluating ground wind loads on the vehicle, tower, and crew access arm, and developing procedures to investigate wind-induced oscillations on the vehicle.

Role of HECC

- In FY21, the Langley team ran over 150 jobs on HECC resources using the Kestrel flow solver with a dual-mesh approach, with each job requiring 1,200 to 3,600 cores over five days.

BENEFIT: These efforts to characterize the aerodynamic environment of the liftoff and transition phases of flight are crucial to developing structurally sound and controllable SLS launch vehicles that can successfully deliver their payloads to orbit and beyond.



"To run one of our small jobs on any of our local systems is impractical, while the hoops we would have to jump through to run one of the larger jobs are insurmountable. Without HECC, we would not be able to run enough CFD simulations to contribute to the development of the SLS." – *Steven Krist, NASA Langley Research Center*

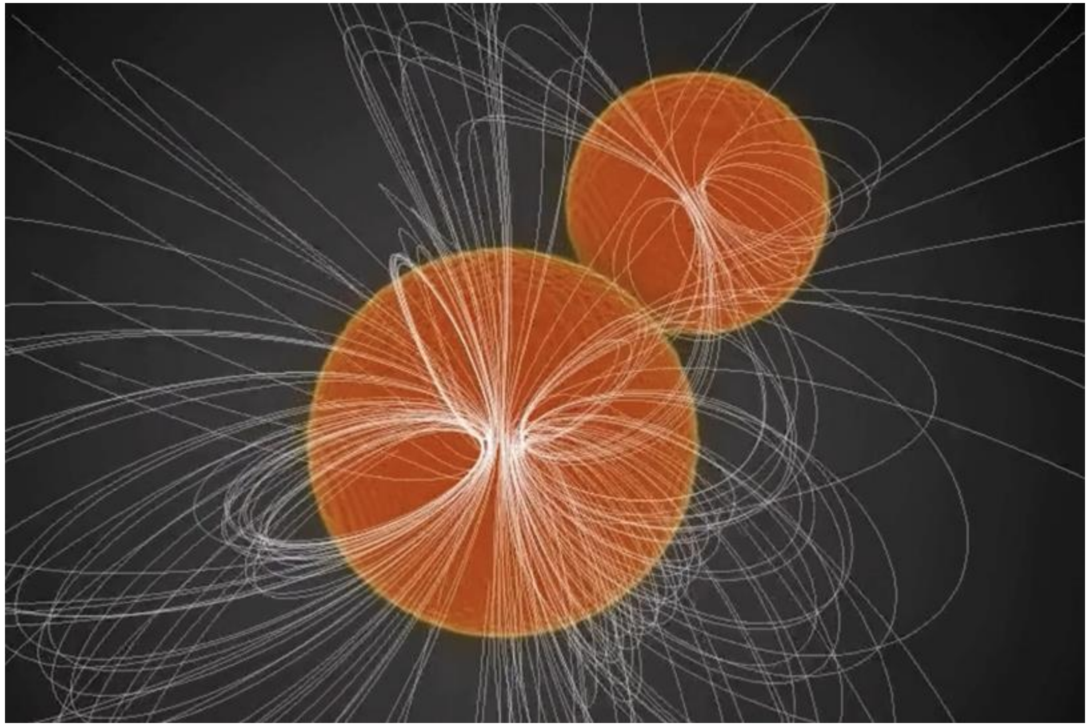
HECC Annual Report FY21

Science Mission Directorate

National Aeronautics and Space Administration

HECC FY2021: Science Mission Directorate

- NASA's leadership role in seeking knowledge and deep understanding of our planet, solar system, and the universe relies on HECC supercomputing resources and technical expertise to support all areas of the agency's science mission.
- In FY21, the investment in HECC systems and services supported 516 SMD projects, providing scientists and engineers with more than 55 million SBUs* to meet program objectives.
- Twenty representative projects are highlighted, including modeling the atmosphere of Mars and exoplanets; supporting NASA's MMS and MAVEN science missions; discovering the effects of air pollution on precipitation; simulating the evolution of galaxies across cosmic time; showing how the ancient Moon's magnetic field may have affected the atmosphere of the early Earth; and developing the latest version of GMAO's seasonal forecast system.
- These 20 projects produced nearly 100 publications and presentations that collectively earned approximately 950 citations.
- Looking ahead, HECC resources and services will continue to play a key role in interpreting data from space-based observatories—helping maximize science return from the newly launched James Webb and the upcoming Nancy Grace Roman Space Telescopes; contributing to asteroid threat assessment efforts; and advancing understanding of the dynamics and effects of climate change.

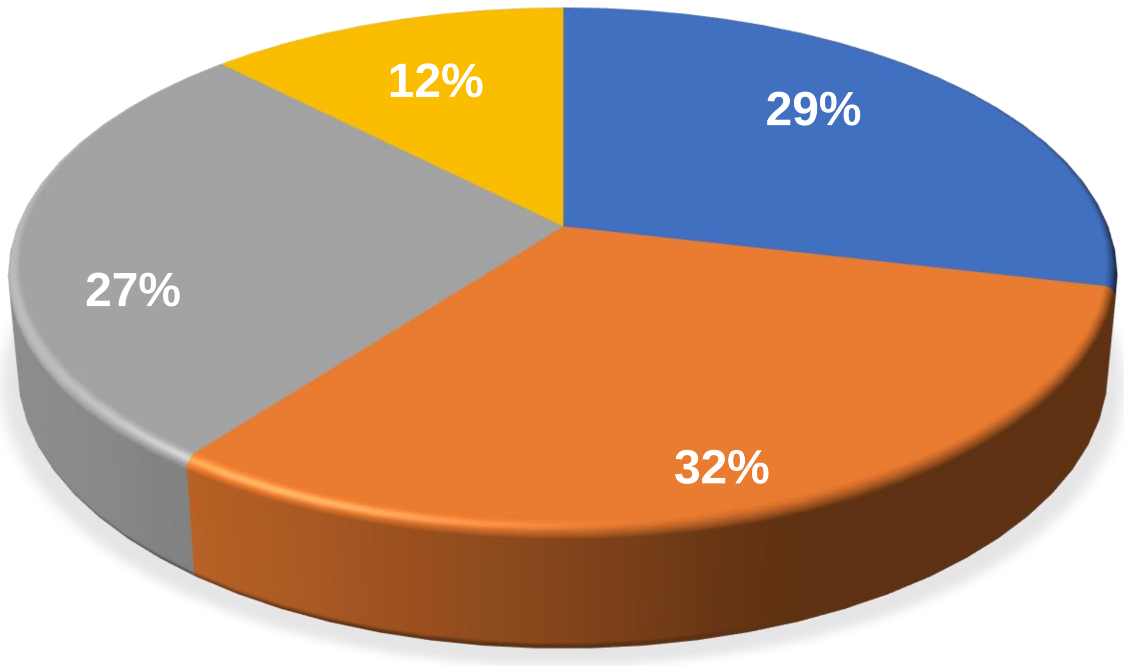


**1 SBU equals 1 hour of a Pleiades Broadwell 28-core node.*

HECC FY 2021: Science Mission Directorate

- **Total Usage:** 56,384,244 SBUs
  - **Total Number of Projects:** 516
  - **Average CPU Range:** 2,049 – 4,096 CPUs
  - **Average Expansion Factor:** 2.01
  - **Agency Reserve:** 6,556,137 SBUs
  - **Share:** 44,319,483 SBUs
  - **Usage as Percentage of Share:** 127%
  - **Usage as Percent of Share + Agency Reserve: 95%**
- **By Program**
  - **Earth Science:** 17,830,832
  - **Astrophysics:** 16,176,207
  - **Heliophysics:** 15,418,391
  - **Planetary Science:** 6,958,814

SMD FY21 Usage



**1 SBU equals 1 hour of a Pleiades Broadwell 28-core node.*

Modeling the Climate of Mars and Mars-like Exoplanets

Summary

- Researchers with the Mars Global Climate Modeling Center (MCMC) project develop, maintain, and provide state-of-the-art Mars Global Climate Models (GCMs) for the scientific community. The MCMC's core functions are to: 1) conduct cutting edge research on the Martian atmosphere and climate, with extensibility to exoplanets; 2) develop and maintain state-of-the-art models; 3) provide access to the models and output; 4) support NASA missions; and 5) educate, engage, and form partnerships with the community.

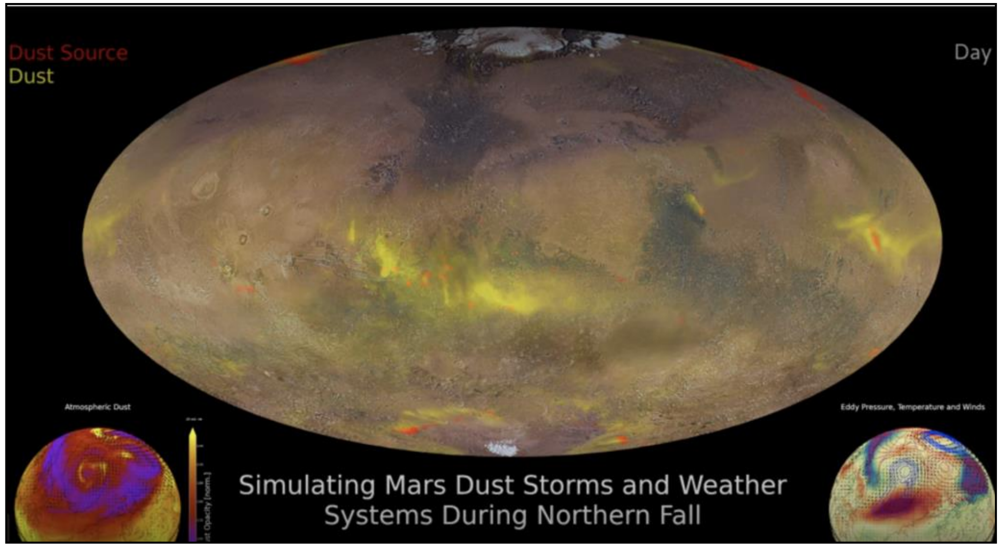
Key Results

- The researchers made significant progress in FY21 on the goals of this multi-year project, including researching key processes of the present-day Mars climate cycles and general circulation, the nature of the early Mars climate, and the nature of climates of Mars-like exoplanets.
- Progress on model development included: improving how aerosols are treated in the GCMs, implementing physics to simulate processes in the upper atmosphere, and implementing physics to simulate the early Mars climate.

Role of HECC

- HECC resources enabled several requirements for the success of this project: high quality simulations, fast visualization of results; high spatial and temporal resolution capability; and fast I/O through highly parallelized computing. In addition, model output is provided to the community via the NAS Data Portal.

BENEFIT: The Mars Global Climate Modeling Center is named in the 2018 NASA Strategic Plan as a capability that contributes to advancing the agency's Strategic Goal 1, "to expand human knowledge through new scientific discoveries." This research supports robotic exploration of Mars, the Mars Sample Return Mission, and future human exploration of Mars.



"HECC resources make our project possible because global climate modeling, particularly at high resolution, is extremely computationally intensive."
– Melinda Kahre, NASA Ames Research Center

Simulating Cosmic Weather within Galaxy Clusters

Summary

- To support one of NASA's goals to better understand the physics of the cosmos, university researchers used HECC systems to develop and analyze large hydrodynamic simulations that can unveil the formation and role of multiphase gas in galaxy groups and clusters. Understanding these processes is crucial to interpreting observations and producing robust, accurate models.

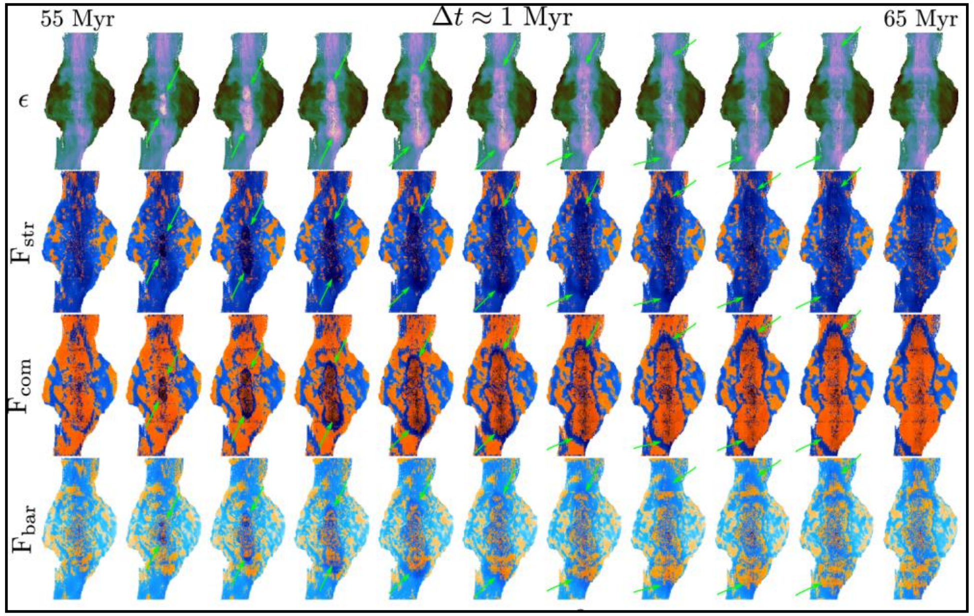
Key Results

- The team studied the 3D turbulent "weather" in high-resolution Eulerian adaptive mesh-refinement simulations of active galactic nucleus (AGN) feedback. The simulations are shown to be consistent with several multiwavelength observations of central galaxies and clusters.
- Simulations of Lagrangian tracers track the evolution of enstrophy (a proxy of turbulence), allowing the researchers to isolate the physical processes that determine the evolution of turbulence. They found that the evolution of enstrophy in the gaseous halo is highly dynamic and variable over small temporal and spatial scales, particularly following AGN feedback activity.

Role of HECC

- Developing these high-resolution simulations over an unprecedented dynamical range required the use of massively parallel computing resources. HECC's mass storage system was also key to enabling analysis of several terabytes of output files.

BENEFIT: These scientific investigations play a key role in advancing our knowledge of cosmic structures and augment the growing field of computational astrophysics in support of NASA observational missions, such as the Chandra X-Ray Observatory and the Hubble and James Webb Space Telescopes.



"NASA's Pleiades supercomputer and other capabilities, including the mass storage system, are fundamental to allow us to achieve the planned astrophysical goals."
— Massimo Gaspari, Princeton University

Supporting NASA’s MMS and MAVEN Science Missions

Summary

- Researchers at NASA Goddard conducted global hybrid and full particle-in-cell simulations to gain insight into the kinetic physics of magnetic reconnection and shocks that have been observed by NASA’s Magnetospheric Multiscale (MMS) and Mars Atmosphere and Volatile EvolutioN (MAVEN) missions.

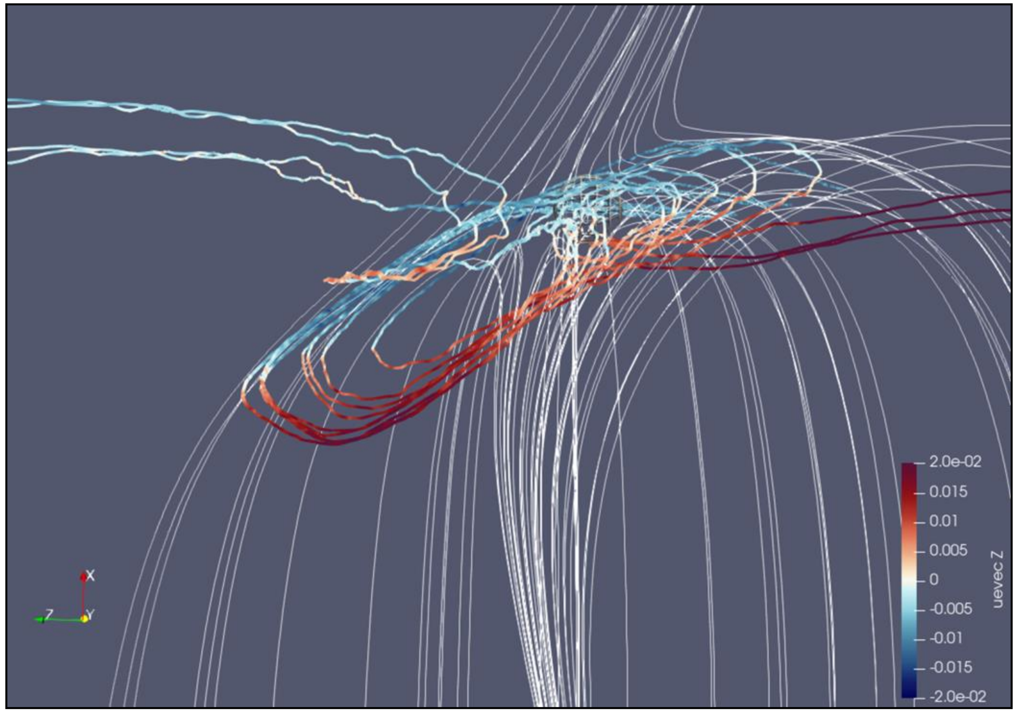
Key Results

- The simulations reveal how planet-sized pulses of magnetic field and density enhancements are generated locally just upstream of the shocked solar wind—even under quiet solar driving conditions—and how these pulses potentially impact magnetospheres by producing holes and indents in Earth’s magnetic shield and presenting global space-weather disturbances to the small induced magnetosphere of Mars. These findings provide a basis to understand MMS and MAVEN mission discoveries, and advance fundamental understanding of solar wind interaction with planetary magnetospheres.
- Results also help to guide science planning for several upcoming missions, including HelioSwarm, Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS), and Psyche.

Role of HECC

- These highly parallel simulations required up to 100,000 cores each (for 3D runs) on the Electra and Aitken supercomputers. Outputs of up to 100 terabytes necessitated the use of HECC storage systems.

BENEFIT: This work supports NASA’s goal to achieve a better understanding of the space environment around Earth and throughout the solar system by helping scientists interpret and guide observations.



“HECC’s supercomputing resources enabled us to conduct the simulations and create the visualizations which help advance MMS and MAVEN mission science.”
— Li-Jen Chen, NASA Goddard Space Flight Center

Air Pollution Impacts on Cloud Formation and Precipitation

Summary

- Scientists at Colorado State University are utilizing observations obtained during NASA's Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP^{2}Ex) field campaign—along with high-resolution mesoscale modeling on HECC supercomputers—to study the impacts of aerosols on the development of clouds, and the subsequent generation of precipitation.

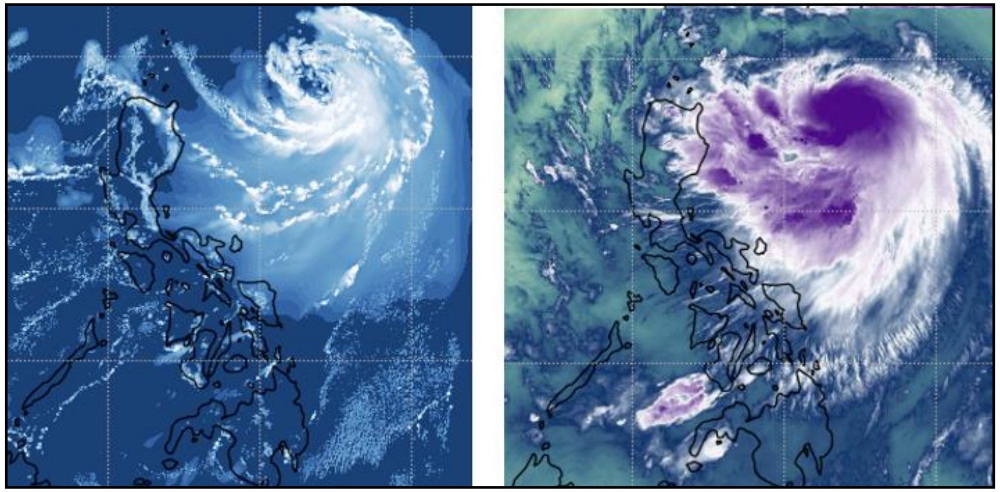
Key Results

- The simulations indicate that increasing aerosol concentrations create more congestus clouds that do not transition to deep convective clouds—resulting in less precipitation overall.
- Analysis of the team's shallow cumulus/congestus cloud simulations shows that with increased aerosol loading, cloud droplets are more numerous but smaller, and raindrops are fewer but larger. However, preliminary results indicate that the impact on precipitation quantity has some dependence on cloud type (for example, congestus vs deep convection), as well as on the magnitude of the aerosol loading.

Role of HECC

- With large-scale simulations utilizing grids comprising 351 million points—and total simulations requiring around 750 terabytes of storage—the Pleiades and Electra supercomputers, along with HECC's massive storage systems, were essential to this work.

BENEFIT: This work provides valuable data that can be used for comparison with data obtained by NASA's CAMP^{2}Ex field study, and also supports many of the aerosol, cloud, convection, and precipitation goals outlined in the 2017 Decadal Survey now being implemented in NASA's Atmosphere Observing System (AOS). Results can also be used to help validate current theory and inform future NASA-driven research on tropical convective clouds.



"Our large-scale simulations would have been impossible without HECC resources. Moreover, help from HECC experts has also been invaluable to improve I/O speeds."
– Susan van den Heever, Colorado State University

How the Ancient Moon Shielded Earth's Atmosphere

Summary

- The Moon has been the Earth's gravitational companion since before humans dwelled on Earth and new research shows that several billion years ago the Moon played a far more important role in protecting the young Earth. Recent reexamination of lunar samples from the Apollo missions indicates that the Moon had a magnetic field in the past. Scientists from Princeton University ran simulations of the interaction between a solar superstorm and the Earth-Moon magnetic field to better understand how the magnetized ancient Moon shielded early Earth's atmosphere.

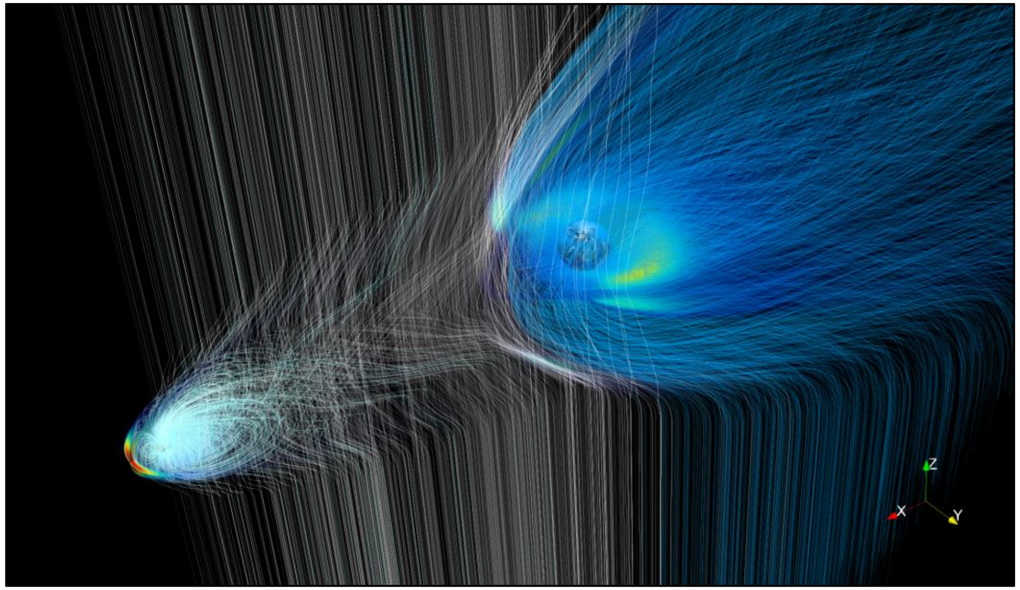
Key Results

- The researchers produced first-of-their-kind multifluid magnetohydrodynamic (MF-MHD) simulations of the entire magnetized Earth-Moon system during an extreme "Carrington-type" space weather event, or solar superstorm.
- The simulations show how the magnetic field of the ancient Moon could have protected Earth from bombardment by a copious amount of solar storm protons, and thus reduced the atmospheric losses from Earth under the period of a highly volatile young Sun.

Role of HECC

- HECC supercomputing resources enabled these first-of-their-kind 3D high-resolution MF-MHD simulations of the entire Earth-Moon system. Each run used 52,000 cores on the Pleiades or Electra supercomputers.

BENEFIT: The ability to simulate a superstorm's passage through the entire young Earth-Moon magnetic field system could revolutionize our understanding of the role of the ancient magnetized Moon on planetary protection and help determine some research areas for the Artemis Program.



"Access to HECC resources makes it possible to perform the large and complex Earth-Moon models required for this work. Future simulation results will be testable via laboratory isotopic analyses of lunar samples brought to Earth by NASA missions."
— Chuanfei Dong, Princeton University

Simulations of Flares from Supermassive Black Holes

Summary

- Using HECC systems, researchers from the University of Colorado Boulder are carrying out 3D general relativistic magnetohydrodynamic (GRMHD) simulations of gas accreting onto black holes.

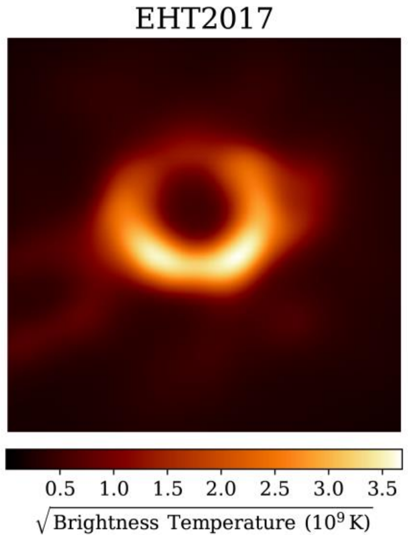
Key Results

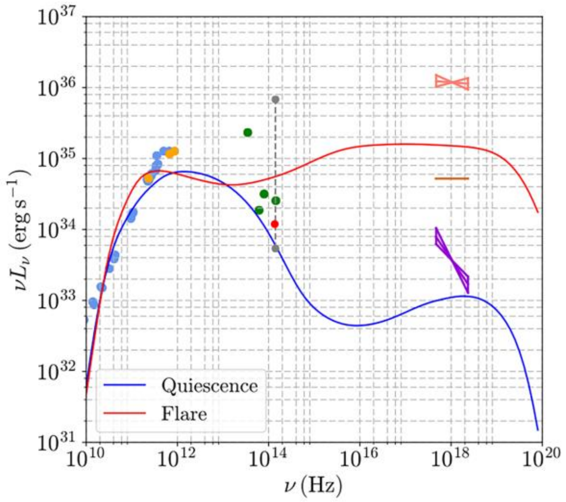
- First-of-their-kind GRMHD calculations for the supermassive black hole in the galaxy M87 led to new predictions for its appearance in imagery taken by the Event Horizon Telescope. They also analyzed the physical and radiation field properties near the black hole to determine if its near horizon might generate gamma-ray flares like those detected by the Fermi satellite.
- They also studied infrared to X-ray flares triggered by magnetic reconnection in strongly magnetized disks, showing that non-thermal particle acceleration can explain the X-ray flares observed in Sagittarius A*, the supermassive black hole at the center of the Milky Way galaxy. By including radiation in their simulations, they can now also study the effects of radiative cooling.

Role of HECC

- Access to the Pleiades, Electra, and Aitken supercomputers have enabled new frontier studies that would not otherwise have been possible. The Lou mass storage system allowed the team to store large volumes of output data, enabling the high cadence data output needed to better understand how these sorts of astronomical systems evolve over time.

BENEFIT: Studying how black holes interact with their environment directly addresses many of NASA's mission goals to study the development of supermassive black holes, active galaxies, and black hole-galaxy co-evolution. These models provide theoretical predictions and interpretations for current missions, such as the Chandra and Fermi satellites, and ground-based experiments like VLTI/GRAVITY and the Event Horizon Telescope.





"HECC resources have been critical for carrying out our research program."
— Jason Dexter, University of Colorado Boulder

New Regimes in 3D Global Modeling of the Sun’s Interior

Summary

- To advance computational capabilities of global solar modeling and promote the advancement of early-career scientists, a research team at New Jersey Institute of Technology (NJIT) and NASA Ames developed a novel 3D global numerical solver of the linearized compressible Euler equations, implemented in a forward modeling approach of helioseismic techniques. NJIT modeling was funded by the Future Investigators in NASA Earth and Space Science and Technology (FINESST) Program.

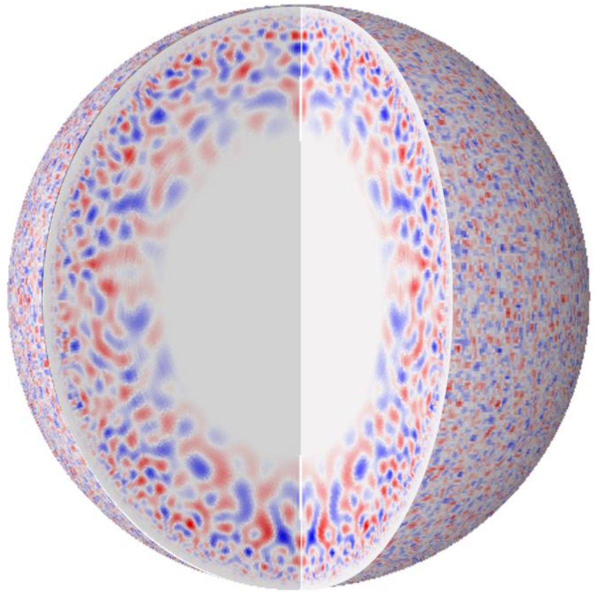
Key Results

- Performed 3D modeling and simulation of acoustic oscillations over background velocity flow fields in the solar interior. Tested resulting synthetic dopplergram products and compared them to observational data from the Solar Dynamics Observatory (SDO).
- The simulations showed that recent inferences positing a single-cell meridional circulation profile may not be correct and put constraints on multi-cell circulation models. Crucially, these models help validate new, efficient, and highly scalable computational techniques representing the future of global high-performance CFD in spherical regimes such as the Sun and stars.

Role of HECC

- The team used thousands of hours on Pleiades to run simulations that would otherwise take years. The simulations are critical foundational tools in physics that will help answer questions integral to our understanding of the universe.

BENEFIT: This new technique is used to generate global synthetic dopplergram data, replicating data products from NASA missions such as the Helioseismic Magnetic Imager on the SDO. Forward modeling helioseismic signatures of known solutions enables better understanding of observational results and the internal solar structures.



“Thanks to HECC resources, for the first time, we were able to simulate acoustic velocity perturbations throughout the solar interior with high resolution.”
— Alexander Kosovichev, New Jersey Institute of Technology

Cloud System Resolving Modeling with GEOS

Summary

- The Global Earth Observing System (GEOS) atmosphere model and the MIT General Circulation Model (MITgcm) ocean model produce global simulations of the highest fidelity and complexity, enabling digital twin prototypes of the Earth system with varying degrees of complexity and resolution. Researchers at NASA Goddard developed improved simulations representing convection, precipitation, aerosols, carbon, and chemistry in the NASA GEOS model.

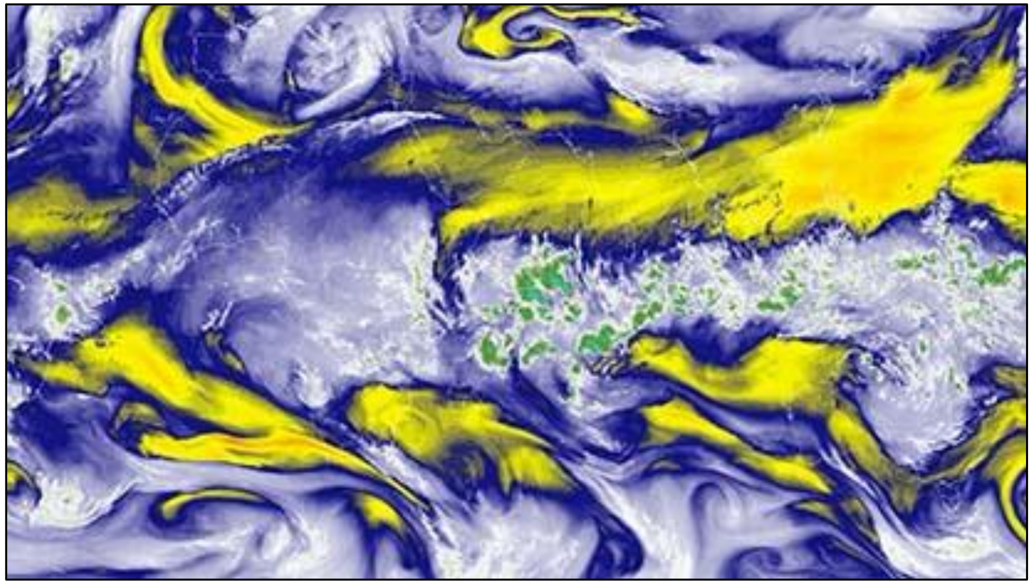
Key Results

- Produced a 1.5-year coupled atmosphere-ocean simulation: 6-kilometer (km), 72-level atmosphere and 4-km, 90-level ocean with interactive, two-moment aerosol cloud microphysics (later extended to a 14-month simulation).
- Produced a 40-day 3-km, 181-level atmosphere+carbon simulation with single-moment, 6-phase cloud microphysics including 1-km global carbon emissions for chemistry transport.
- Produced a 40-day 1.5-km, 181-level atmosphere simulation with simple parameterized chemistry.

Role of HECC

- HECC supports the exploration of traditional hybrid parallelism and prepares NASA models for future HEC platforms by exposing new depths of parallelism and scalability.

BENEFIT: These simulations explicitly resolve atmospheric convection and geostrophic turbulence in the ocean, producing better simulations of clouds and precipitation in the atmosphere, deep water formation, global currents in the ocean, and the fluxes that occur at the ocean-atmosphere interface.



"HECC is providing essential resources for preparing our modeling systems for emerging supercomputing systems and exploring new science developments."
— William Putman, NASA Goddard Space Flight Center

Mars Sample Return: Earth Entry Vehicle Aerodynamics

Summary

- The success of NASA's Mars Sample Return mission, a flagship mission to return samples of Martian rock and soil to Earth, is dependent on the successful landing of its Earth Entry Vehicle (EEV), which will enter our planet's atmosphere at 11 kilometers per second and decelerate to subsonic velocity without a parachute. To understand the EEV's entry aerodynamics, NASA Langley researchers ran computational fluid dynamics (CFD) simulations using the FUN3D and US3D codes on HECC supercomputers.

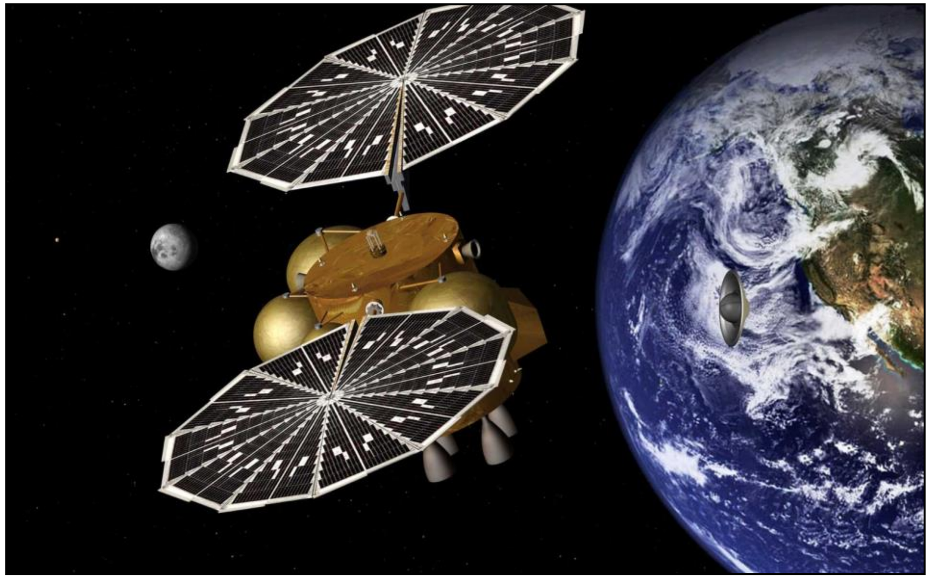
Key Results

- Results of key CFD simulations were used to populate the aerodynamic database used by flight simulation engineers in Monte Carlo analyses—the primary tool used to predict flight performance and identify risks. In addition, simulations of a test configuration in Langley's Transonic Dynamics Tunnel helped improve understanding of the experimental flowfield and reduce aerodynamic uncertainties.

Role of HECC

- Static aerodynamic coefficients for various iterations of the flight vehicle were typically run on 1,000 cores of the Pleiades system at flight conditions ranging from low subsonic (Mach 0.1) to hypersonic (Mach 5) over flight-like angle of attack ranges, and to simulate various wind tunnel tests at sub- and transonic conditions—a substantial range of studies that required HECC resources.

BENEFIT: Simulations run on HECC systems are critical to understanding the aerodynamics of the Mars Sample Return mission's Earth Entry Vehicle. Results are applied to vehicle development and understanding wind tunnel test results; and within flight simulations to characterize flight performance and risk.



"HECC resources enable and accelerate our work by providing large core counts and longtime scales which aren't available on other compute resources."
— John Van Norman, NASA Langley Research Center

Simulating the Evolution of Galaxies Across Cosmic Time

Summary

- Astrophysicists from the Space Telescope Science Institute and Johns Hopkins University use HECC resources to run cosmological hydrodynamic simulations, using their "Figuring Out Gas & Galaxies In Enzo (FOGGIE)" code, to trace the co-evolution of galaxies and their gas over 13.7 billion years of cosmic time. These high-resolution, realistic simulations of galaxies help interpret data from observations and make predictions for the difficult-to-observe parts of galaxies.

Key Results

- With high resolution applied to both the stars and gas within galaxies, the researchers achieved unprecedented precision in their simulations—at least an order of magnitude improvement over previous generations.
- The teams developed a new model for calculating the expected temperature of a virialized galaxy halo, which has significant ramifications for data obtained by observatories. They also completed four production simulations that will enable the Nancy Grace Roman Space Telescope project team, and the wider astronomical community, to understand how Roman observations will explore nearby galaxies with its very large fields of view and superb image quality.

Role of HECC

- The FOGGIE research requires HECC resources at every stage: creating initial conditions, running the simulations, and visualizing and analyzing the results—all problems that require high-performance computing and storage.

BENEFIT: This project provides detailed theoretical predictions for NASA's upcoming Nancy Grace Roman Space Telescope—including simulated galaxies and mock data specifically intended for Roman—and for the James Webb and Hubble Space Telescopes. The work addresses NASA's strategic goal to understand the universe.

"These extremely challenging simulations would be impossible without HECC compute and storage resources. Moreover, we relied on the irreplaceable HECC visualization team to implement our data pipeline and create movies for analysis." – *Jason Tumlinson, Space Telescope Science Institute/Johns Hopkins University*

Electron Heating and Plasma Emission in the Solar Corona

Summary

- Nanoflares heating is recognized as an important process contributing to the heating of the solar corona, especially to electron heating in the lower corona. Researchers at The University of Alabama in Huntsville (UAH) ran supermassive particle-in-cell (PIC) simulations to address two fundamental, unsolved questions about particle heating and acceleration in flares.

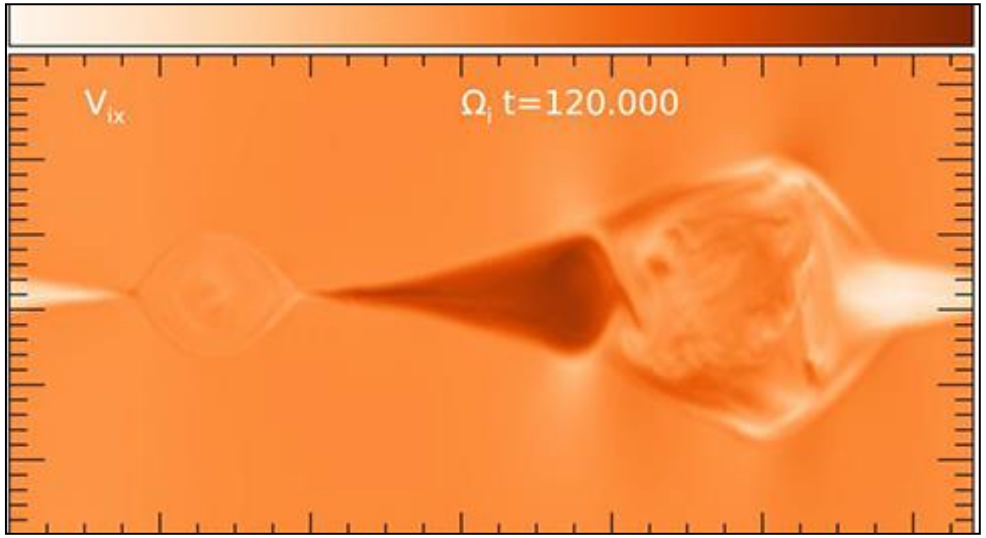
Key Results

- To study how guide field magnetic reconnections (MRs) produce particle outflows/beams, the UAH team produced simulations of PIC acceleration in MR, showing for the first time that in force-free reconnection, the development of an electron Kelvin–Helmholtz instability (EKHI) can suppress the Hall effect and produce a flute-like outflow exhaust as well as fast electron and ion jets.
- Ions can be efficiently accelerated to the power-law energy distribution in solar flares by driving EKHI during MR, with the study's results showing that ions are significantly accelerated by the coupling between the EKHI-induced stochastic electric field and Alfven turbulence as the magnetic vortices expand to sizes comparable to the ion gyroradius.

Role of HECC

- HECC supercomputers enabled supermassive PIC simulations that trace billions of charged particles and produce large amounts of data, requiring HECC's large nobackup disk space.

BENEFIT: This work directly relates to the Parker Solar Probe and Solar Dynamics Observatory science goals to study nanoflare heating; and to goals of the Heliophysics Decadal Survey to predict the variations in space and the fundamental processes within the heliosphere and throughout the universe.



"Our research was made possible using NASA's supercomputing resources. The efficient and high-quality support of HECC experts accelerates the carry-out and analyzation of these simulations."
—Haihong Che, The University of Alabama in Huntsville

Subseasonal to Decadal Climate Forecasts (GEOS-S2S-3)

Summary

- NASA's Global Modeling and Assimilation Office (GMAO) developed subseasonal prediction systems that are designed to demonstrate the beneficial impact on the forecast predictability and prediction skill of including additional interactive Earth system components in the model; increased resolution and forecast ensemble size; and forecast initialization from a modern assimilation that incorporates new ocean data types. This activity relied heavily on the availability of HECC computing resources.

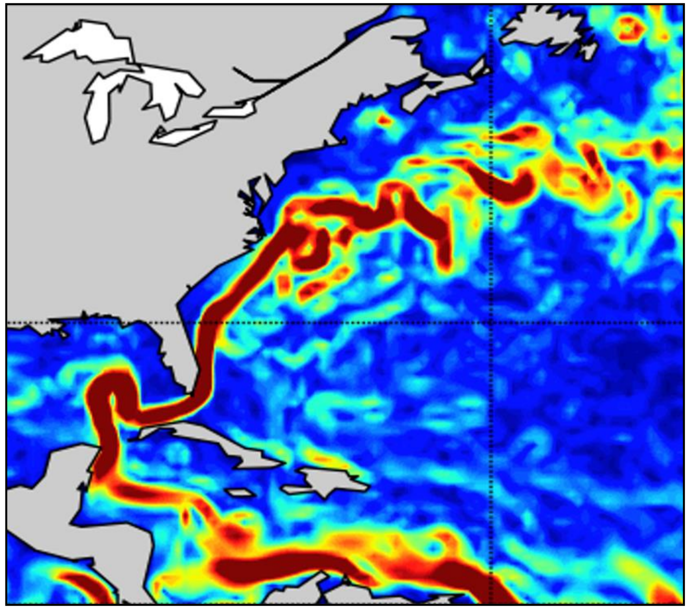
Key Results

- The new version of GMAO's seasonal forecast system, GEOS-S2S-3, includes higher ocean resolution and a larger ensemble size. Among the advantages of increased ocean resolution are more realistic surface currents and ocean transport; and the new ensemble strategy provides more skillful forecasts and more accurate predictability estimates. This unique suite of forecasts is generating substantial interest in the scientific community as a research tool for studying predictability.

Role of HECC

- HECC resources were essential for timely validation and delivery of the new version of GEOS-S2S-3, which entails a suite of retrospective forecasts. Each nine-month duration forecast required 180 hours of wall-clock time on 122 Skylake nodes for a single month of simulation, and typically required 8–10 forecasts to run concurrently.

BENEFIT: NASA's Global Modeling and Assimilation Office uses GEOS-S2S-3, in conjunction with satellite and in situ observations, to study and predict phenomena that evolve on seasonal to decadal timescales, and to improve model forecast capability.



"We relied heavily on the availability of HECC computing resources, which allow GEOS-S2S-3 to improve forecast predictability and prediction capability in part by increasing ensemble members and resolution."
— Andrea Molod, NASA Goddard Space Flight Center

Following Gravitational Collapse of Forming Planetesimals

Summary

- Researchers at the University of Nevada, Las Vegas used HECC resources to run large-scale magnetohydrodynamics simulations modeling the gas and dust grains in protoplanetary disks to study their interaction and dynamics and to deduce the conditions for forming kilometer-sized planetesimals that are the building blocks of planets.

Key Results

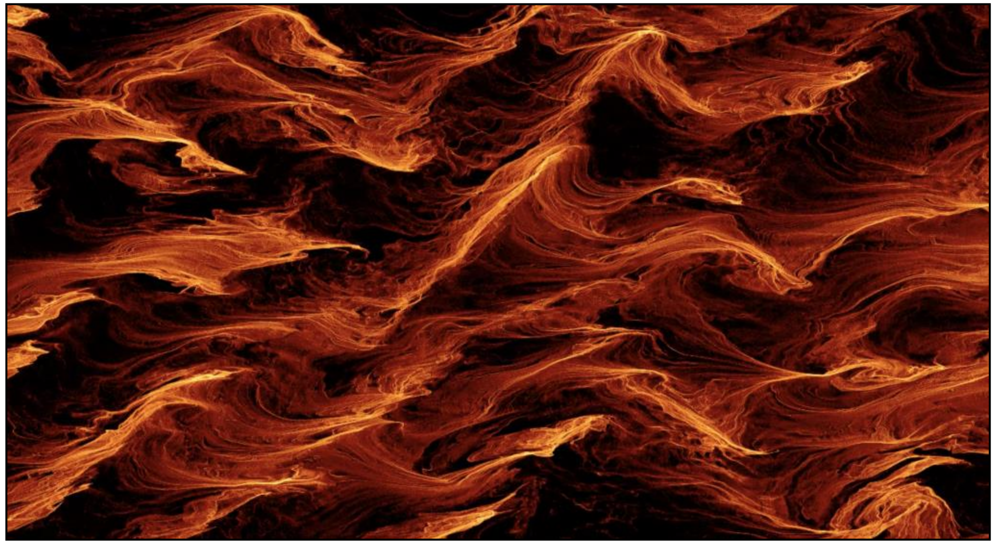
- The large-scale simulations captured disk dynamics, including a phenomenon that showed a protoplanetary disk orbiting binary stars can align itself in an orbit perpendicular to the orbit of its host stars under certain conditions. The simulations also showed that the gravity from the host stars sends ripples through the disk, causing it to twist, warp, and sometimes break into pieces.

- The team also generated several different synthetic observations that predicted the dust grains should be either very small or moderately porous. Many disk sizes and ages prefer larger grains, implying that the latter scenario is more likely. These inferences help constrain the initial conditions for forming planetesimals, improving the accuracy of modeling efforts.

Role of HECC

- In order to accurately simulate protoplanetary disk evolution at the highest resolutions, the team uses millions of hours parallelized across thousands of processors on the Pleiades and Electra supercomputers.

BENEFIT: These studies at all scales of the planet formation process—the initial size distribution of the grains, how the grains collect together, and the evolution of the protoplanetary disk as a whole—are relevant to NASA missions exploring Kuiper Belt objects, asteroids and comets, including New Horizons, Lucy, and OSIRIS-REx, and the NASA-supported international mission, Rosetta.



"It would be virtually impossible to achieve our models and simulations without HECC resources."
— Chao-Chin Yang, University of Nevada Las Vegas

General Relativistic Simulations of Binary Neutron Stars

Summary

- The numerical relativity group at the University of Illinois at Urbana-Champaign is using HECC resources to simulate the inspiral and merger of magnetized neutron star systems. These complex simulations are used to model gravitational waves and to explain electromagnetic signals such as short gamma-ray bursts that can be detected by NASA spacecraft, as well as to gain a better understanding of these observations and the physics of matter under extreme conditions.

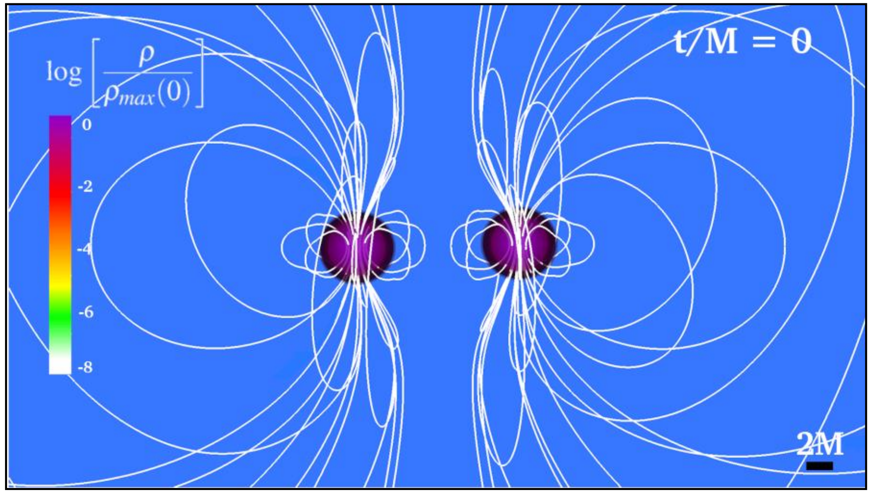
Key Results

- Using their in-house general relativistic magnetohydrodynamics (GRMHD) code, the researchers achieved the first numerical simulation of magnetized neutron star binaries showing that these systems can launch magnetically-driven jets, and the first numerical simulation of supermassive black hole binaries with different mass-ratio and spins.
- Results show that binary neutron star mergers can be progenitors of short gamma-ray bursts if the merger undergoes delayed collapse into a black hole.

Role of HECC

- Simulations involving general relativity are extremely complex, requiring immense computing resources. Each simulation ran on Pleiades for around five months. HECC experts significantly assisted the researchers by improving code performance and helping shepherd the runs through the system.

BENEFIT: Simulations of binary neutron stars advance understanding of these phenomena and are used to model gravitational waves. They also help analyze data obtained by NASA's space-based observatories including the Neil Gehrels Swift and Chandra X-ray Observatories, the Fermi Gamma-ray, James Webb, and Hubble Space Telescopes, and the Neutron star Interior Composition Explorer (NICER) instrument aboard the International Space Station.



"Our codes perform better on HECC systems than on other clusters. On Pleiades, we observe perfect scaling up to 96 nodes and around 85% scaling to 128 nodes, compared with around 80% scaling on 64 nodes on other HPC systems."
— Milton Ruiz, University of Illinois at Urbana-Champaign

Simulating the Split Personalities of Our Sun

Summary

- Using leading-edge 3D magnetic fluid simulations, researchers at the University of Colorado Boulder developed models that capture several cyclical features of solar magnetism, and the remarkable propagation of magnetic flux toward the poles. The simulations suggest that the Sun may be a chaotic dynamical system residing in a state of bistability—a bifurcation regime in which two distinct dynamos can operate simultaneously or in tandem.

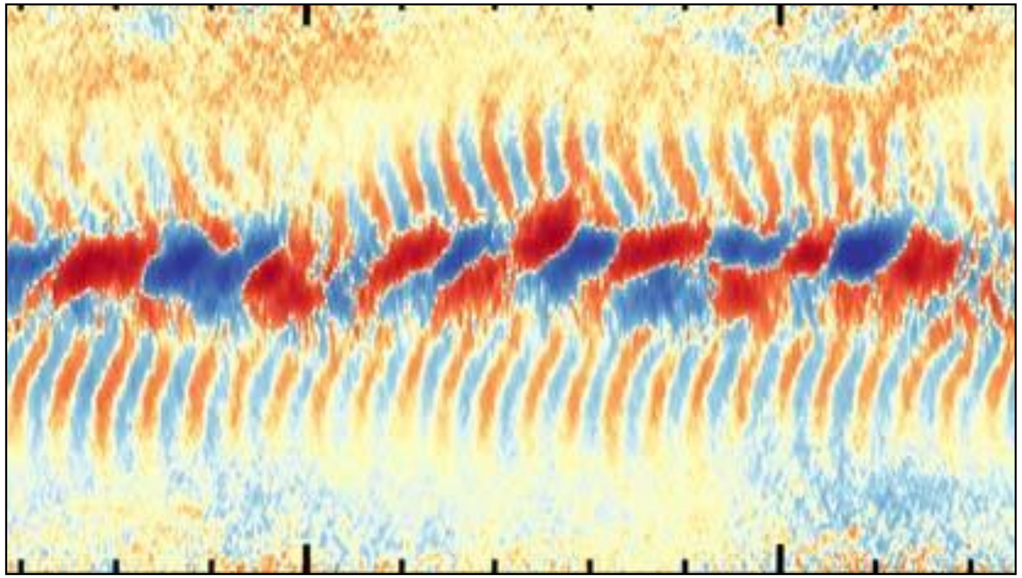
Key Results

- Simulations achieved remarkable dynamo behaviors similar to observed features of the solar cycle:
  - A highly regular cycling system of four “magnetic wreaths”—tubes of magnetic flux that wrap all the way around a magnetized spherical shell in a large torus—steadily migrate toward the solar equator and regularly reverse their polarity, similar to the butterfly pattern found in the 11-year sunspot cycle.
  - The poloidal magnetic field eventually bifurcates: the system of four wreaths persists and cycles, but a new system of partial wreaths, each of opposite polarity, coexists superimposed on the original system.

Role of HECC

- These simulations often run for weeks at a time and use up to 4,000 processors on the Pleiades supercomputer, producing terabytes of data that require the the Lou mass storage system’s data analysis nodes.

BENEFIT: These simulations provide major insights into how the solar dynamo operates and show that our Sun potentially exists in a “bistable” state, where these structures cycle superimposed on one another.



“Simulations like ours show the essential role played by the agency’s advanced computing infrastructure in solving big problems like the very complex and often chaotic solar dynamo.”
— Loren I. Matilsky, JILA / University of Colorado Boulder

Advancing NASA's Modeling for Precipitation Prediction

Summary

- Researchers at NASA Goddard conducted numerical simulations using the Goddard Multi-scale Modeling Framework (GMMF)—a super-parameterized global cloud-permitting model—to investigate precipitation intensity of different sized precipitation systems and their impact on weather and short-term climate changes. The goal: to utilize NASA satellite products and field campaign data to validate and improve cloud and precipitation processes in the cloud-resolving Goddard Cloud Ensemble model (GCE) and the GMMF.

Key Results

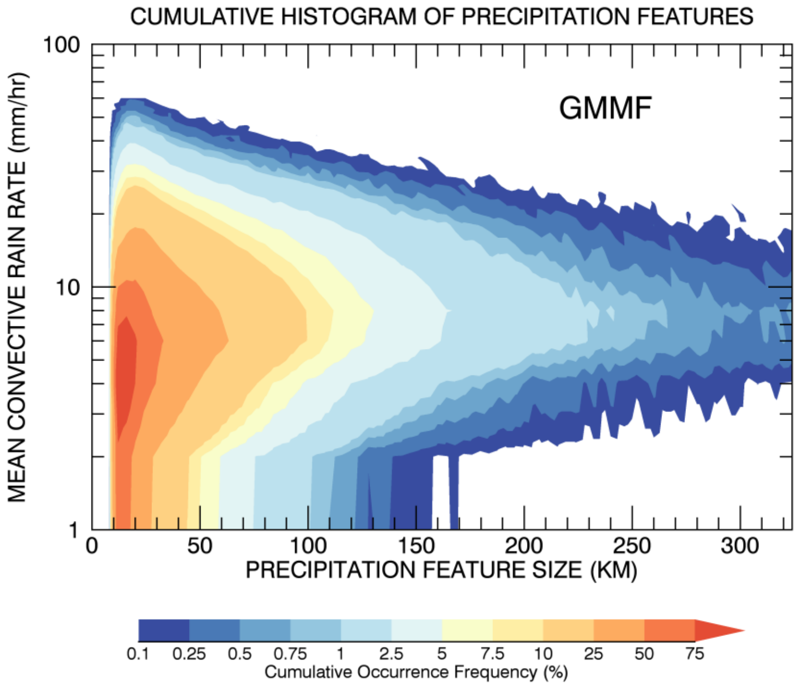
- Several long-term GCE simulations using three different microphysical schemes were conducted, and results were compared with Global Precipitation Measurement Mission (GPM) satellite observations showed that the model can simulate the transition from shallow cloud to deep convection.

- Many yearly GMMF simulations with different combinations of GCE grid spacings and domain sizes were performed to investigate the characteristics of global and regional precipitation features. The simulations are in good agreement with Tropical Rainfall Measuring Mission (TRMM) observations.

Role of HECC

- Several one-year GMMF integrations with different resolution were conducted using 2,048 cores on Pleiades. The GMMF requires substantial computing time (~500 times that of traditional climate models) and disk space. Without HECC resources, this project could not be carried out in a timely fashion.

BENEFIT: Validation and improvement of precipitation intensity and associated physical processes for different sizes of precipitation systems are crucial to weather forecasting and future climate projection.



"The HECC supercomputers and mass storage systems enable us to run a high-resolution global model that explicitly resolves storms."
—Wei-Kuo Tao, NASA Goddard Space Flight Center

Simulating Stellar Impact on the Evolution of Planets

Summary

- Researchers from Newcastle University used the computational power of HECC systems to look at how the dynamical processes inside stars could affect the evolution of planets around them. In FY21, the team looked at the convective generation of internal gravity waves in 2D and 3D simulations to better understand how these waves affect the stellar surface rotation, in order to address how dynamical processes that arise within the star can cause the stellar surface to rotate differently than expected.

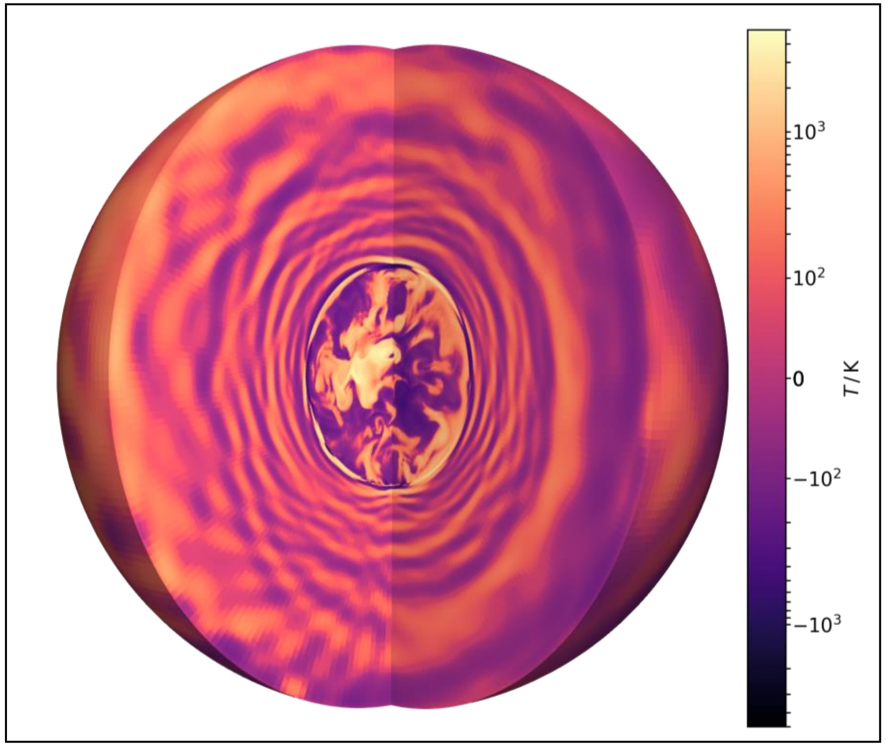
Key Results

- Most of the achievements in the last year revolved around looking at how these processes change over stellar age and mass. Extending the initial work on 3 solar mass stars to 7, 10, 13, and 20 across a variety of different ages allowed the team to develop prescriptions for how these processes can be implemented in 1D stellar evolution codes to better understand the overall effect. They have found that younger stars are more likely to show rotational effects at their surface.

Role of HECC

- These simulations mainly ran on the Pleiades supercomputer's Ivy Bridge processors and generated a huge amount of data. Access to HECC supercomputing resources and expert assistance from staff have been crucial to the team's research.

BENEFIT: This work is part of fundamental research into the evolution of stars and exoplanet systems, driving our understanding of those systems, and helping us understand our own star and the evolution of planetary systems.



"My team has used a variety of HPC systems, but the NASA system is the fastest, best, and easiest to use."
— Tamara Rogers, Newcastle University

Simulating the Birth and Infancy of a Fast Radio Burst

Summary

- The recent discovery of Fast Radio Bursts (FRBs)—intense pulses of radio emission lasting a few milliseconds—has opened a new area of inquiry in high-energy astrophysics. Young, magnetized neutron stars known as magnetars have been identified as a possible source of FRBs; however, the emission mechanisms remain unknown. Astrophysicists from Columbia University ran particle-in-cell (PIC) simulations on the Pleiades supercomputer to investigate these cosmic phenomena.

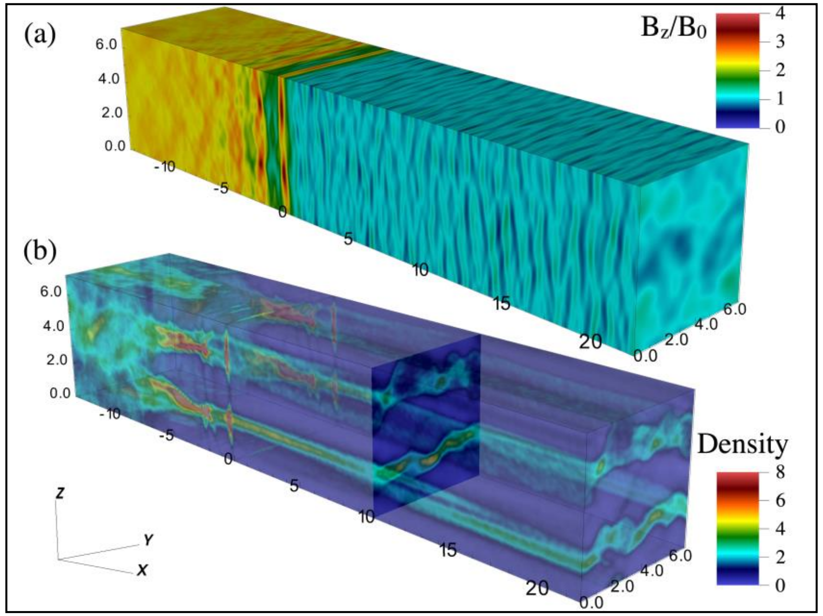
Key Results

- The researchers successfully ran 2D and 3D PIC simulations of relativistic magnetized shocks to assess how the efficiency, spectrum and polarization of FRB emissions depend on the local plasma conditions.
- Results of their work provide information essential to our understanding of FRBs and can provide physically-grounded inputs for FRB emission models based on maser emission from relativistic shocks.

Role of HECC

- Large-scale 3D PIC simulations are required to reliably assess the polarization properties of FRBs. This work is fundamentally based on these complex simulations, which would not be possible without HECC compute resources, storage system, and services.

BENEFIT: This work supports NASA's goal in astrophysics to "Discover how the universe works and explore how it began and evolved." The simulation results support several NASA missions that observe Fast Radio Bursts, including the Neil Gehrels Swift Observatory, the Chandra X-ray Observatory, and the Fermi Gamma Ray Space Telescope.



"This work would not be possible without HECC resources. In addition, HECC experts were enormously helpful in optimizing our code for the computing and storage we required." — *Lorenzo Sironi, Columbia University*

Simulating Solar Wind-Magnetosphere Interactions

Summary

- In order to understand the interaction between solar wind and the terrestrial magnetosphere, researchers from Auburn University developed a simulation code combining their 3D global hybrid model (ANGIE3D) and the Comprehensive Inner Magnetosphere-Ionosphere (CIMI) model from NASA Goddard Space Flight Center.

Key Results

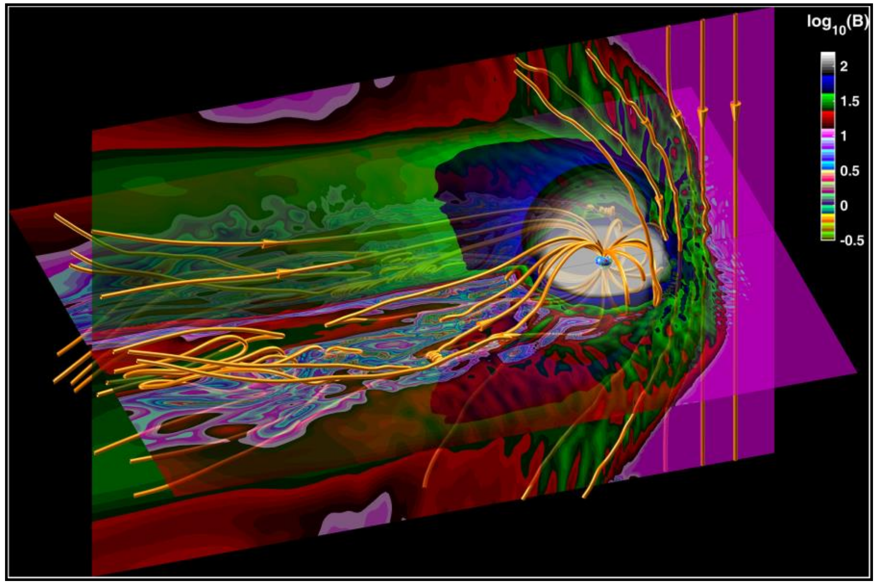
- The team's work showed that under a steady southward interplanetary magnetic field, magnetotail reconnection is localized and recurs within a period of several minutes, resulting in recurring, localized fast flow injections. Multiple fast flow injections lead to multiple peaks in the particle fluxes in the inner magnetosphere and layers of field-aligned currents in the ionosphere.

- ANGIE3D simulations for the interaction of the bow shock with directional tangential discontinuities led to the discovery of global asymmetry of hot flow anomalies (HFAs). The team's results indicate that these transients must exhibit north-south and dawn-dusk global asymmetries for general interplanetary magnetic field conditions.

Role of HECC

- The team relied on parallel computation, with each large-scale particle computation/simulation requiring thousands of cores on HECC systems.

BENEFIT: This work is part of the Heliophysics Research Program investigation combining theory, modeling, and simulations. The success of 3D global kinetic modeling will impact broader planetary simulation efforts and add to the return from NASA spacecraft data.



"HECC is crucial for the work. Without the HECC support—from computation resources to technical personnel—we could not have made the progress and discovery and could not have gained the understanding we achieved. We are very grateful to the wonderful support from HECC."
— Yu Lin, Auburn University

Multi-Scale Modeling For Extreme Weather and Climate

Summary

- Researchers at NASA Goddard conducted multi-scale weather and climate simulations, with two primary science goals: 1) to understand the origin and evolution of precipitation multi-bands in winter storms and 2) to understand how smoke is transported into the stratosphere and what factors control its lifetime, which has radiative impacts on the planet.

Key Results

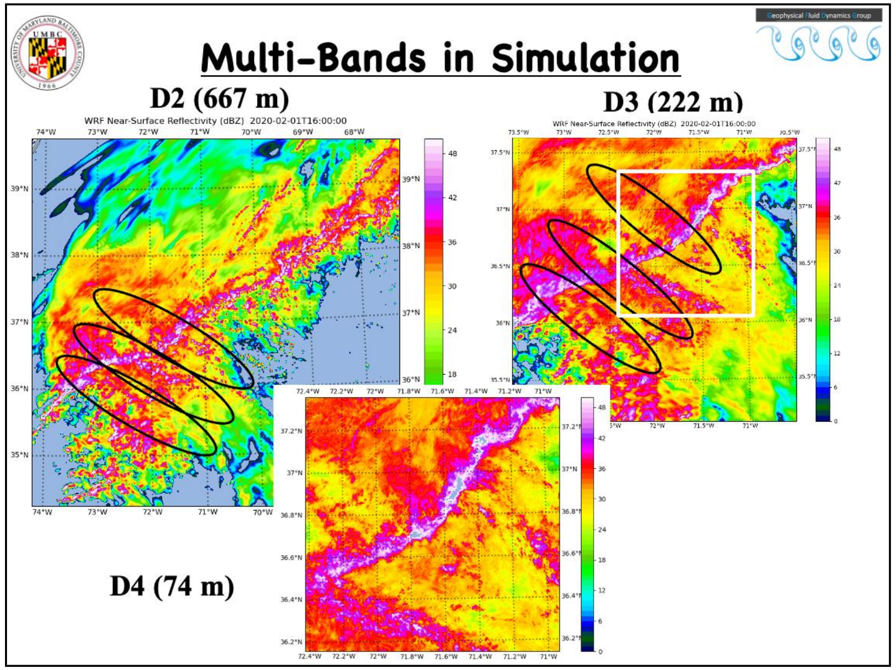
- A Weather Research and Forecasting (WRF) simulation of an extratropical cyclone (grid spacing from 2000 meters down to 74 meters), sampled by the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign, provides critical data for understanding the context of remote sensing measurements collected by a variety of instruments.

- A numerical convergence study of the Goddard Earth Observing System (GEOS) model for a wildfire smoke plume event that occurred in British Columbia in 2017 was conducted with grid spacings of 2 degrees, 1 degree, 0.25 degrees, 7 km, and 7 km-nonhydrostatic. This series of data improves understanding of the smoke lofting and stratospheric lifetime effects.

Role of HECC

- The Pleiades supercomputer has been critical for enabling these simulation results to advance science and further NASA's mission.

BENEFIT: These successful simulations provide critical data to advance the science of weather and climate, and to understand each modeling system, including the Goddard Earth Observing System model.



“No other system at NASA is better for enabling this science and technology work. The number and speed of computing cores as well as the storage and technical assistance from the support team, has been excellent.”
— Stephen Guimond, NASA Goddard Space Flight Center

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